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Report 77-0073

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

THE XBQM-108A VERTICAL ATTITUDE TAKEOFF AND LANDING VEHICLE

by

W. H. Eilertson

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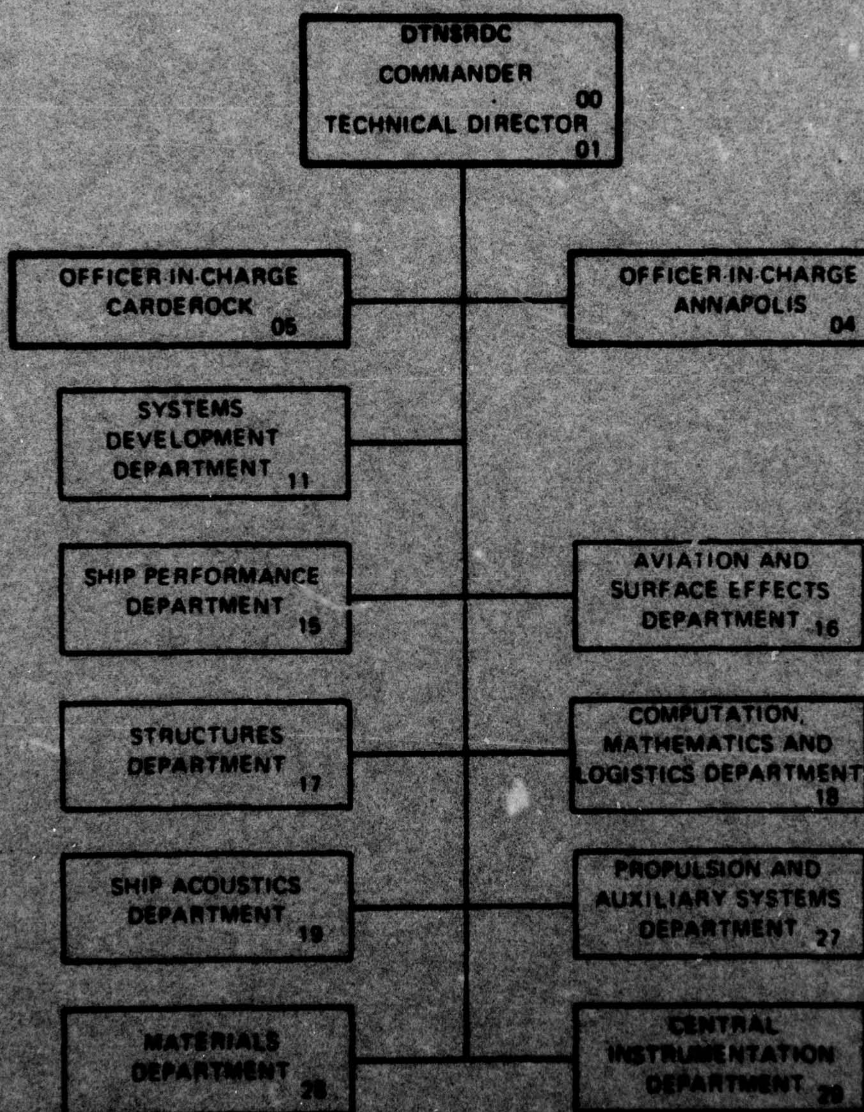
AVIATION AND SURFACE EFFECTS DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

August 1977

Report 77-0073

THE XBQM-108A VERTICAL ATTITUDE TAKEOFF AND LANDING VEHICLE

MAJOR DTNSRDC ORGANIZATIONAL COMPONENTS



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (14) DTNSRDC-77-0073	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) THE XBQM-108A VERTICAL ATTITUDE TAKEOFF AND LANDING VEHICLE.		5. TYPE OF REPORT & PERIOD COVERED (9) Final rept.,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) W. H./Eilertson, VATOL RPV Project Engineer, Aviation and Surface Effects Department		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship Research and Development Center Bethesda, Maryland 20084		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (See reverse side)
11. CONTROLLING OFFICE NAME AND ADDRESS David W. Taylor Naval Ship Research and Development Center Bethesda, Maryland 20084	(11)	12. REPORT DATE August 1977
		13. NUMBER OF PAGES 50
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) (16) F61412, F41421 (17) ZF61412001, WF41421200		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report) (12) 51p.

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

387 682

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Remotely piloted vehicles	Ship interface
Jet vanes	Aircraft
Vertical takeoff and landing	Delta wings
Close-coupled canard	Cruise missile threat

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

To assess the advantages of vertical attitude takeoff and landing, the Aviation and Surface Effects Department at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) designed and constructed a 560-lb demonstration vehicle (designated the XBQM-108A). The design incorporates a close-coupled canard/delta wing configuration that utilizes components from the MQM-74A target drone as well as the Harpoon missile. During the summer

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(Block 10)

DTNSRDC (IED FY-74) Task ZF61412001, Element 62756N, Work Unit 1606-002
DTNSRDC (IED FY-75) Task ZF61412001, Element 62766N, Work Unit 1610-002
DTNSRDC (IED FY-76) Task ZF61412001, Fund Code 09400, Work Unit 1612-002
NADC (IED FY-7T) Task WTW01, Fund Code 61018, Work Unit 1660-860
NAVAIR (PMA 247) Project 63251N, Task WTW01, Work Unit 1-1660-840
NAVAIR (320D FY-7T) Task WF41421200, Fund Code 25613, Work Unit 1660-860

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of 1976 this vehicle was successfully flight tested to assess vertical hover capability in a tethered hover flight mode. Other Navy laboratories cooperated in support of engine installation design and test (Naval Weapons Center), and guidance and control (Naval Underwater Systems Center). Free-flight tests in hover and ship docking are planned. The need for vertical takeoff capability is due to the current threat imposed on the Fleet by the advent of high-speed cruise missiles. This has increased the importance of dispersing aircraft to nonaviation ships should the need arise. The launch and recovery of RPV's and V/STOL manned aircraft aboard nonaviation ships has been identified by the Navy as a major design impact area. Vertical attitude takeoff and landing (VATOL) offers attractive advantages in that ship/aircraft interface docking problems are alleviated. The VATOL airframe design is lighter and cheaper than other candidate concepts and has *superior performance.*

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ABSTRACT

To assess the advantages of vertical attitude takeoff and landing, the Aviation and Surface Effects Department of the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) designed and constructed a 560-lb demonstration vehicle (designated the XBQM-108A). The design incorporates a close-coupled canard/delta wing configuration that utilized components from the MQM-74A target drone as well as the Harpoon missile. During the summer of 1976 this vehicle was successfully flight tested to assess vertical hover capability in a tethered hover flight mode. Other Navy laboratories cooperated in support of engine installation design and test (Naval Weapons Center), and guidance and control (Naval Underwater System Center). Freeflight tests in hover and ship docking are planned. The need for vertical takeoff capability is due to the current threat imposed on the Fleet by the advent of high-speed cruise missiles. This has increased the importance of dispersing aircraft to non-aviation ships should the need arise. The launch and recovery of RPV's and V/STOL manned aircraft aboard nonaviation ships has been identified by the Navy as a major design impact area. Vertical attitude takeoff and landing (VATOL) offers attractive advantages in that ship/aircraft interface docking problems are alleviated. The VATOL airframe design is lighter and cheaper than other candidate concepts and has superior performance.

ADMINISTRATIVE INFORMATION

This project was initiated at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) in FY 1973. From FY 1973 to FY 1976 the project was supported at DTNSRDC under funding provided by the Independent Exploratory Development (IED) program. In FY 1976 additional funds were supplied by the Naval Air Development Center (IED) and the Naval Air Systems Command (PMA 247), Project 63251N, Task WTW01, and Work Unit 1-1660-840.

This study was conducted prior to the adoption of a metric unit policy. In the interest of time and economy, conversion to metric units has not been made.

INTRODUCTION

Vertical takeoff and landing capability is now being assessed by the Navy for both manned and unmanned aircraft. In the unmanned aircraft sector, progress in the development of lightweight avionics has

been the stimulus behind recent Navy interest in remotely piloted vehicles (RPV's). Analyses have indicated that RPV's can be as much as 60 percent lighter and cost only one-third as much as comparable manned aircraft suitable for similar missions. Unmanned RPV's can be designed to fly long endurance missions unencumbered by the constraints imposed on manned aircraft and to be highly maneuverable against heavily defended targets. This can significantly reduce pilot attrition when manned aircraft are lost during such missions. The advantages attributed to RPV's can enhance Navy air support capabilities and can favorably complement manned aircraft. However, RPV's will not replace manned aircraft in support missions requiring higher reliability in engaging targets that pose an immediate threat to the Fleet.

CRUISE MISSILE THREAT

Over the horizon targeting (OTH) is one mission that the Navy has recently identified as suitable for RPV's. It has also been determined that vertical launch and recovery will enable these new RPV's to operate from nonaviation ships. The OTH mission has increased importance because of the threat[1] represented by the Soviet buildup of offensive capability through the use of cruise missiles. This is having a profound effect on naval tactics. Captain Ruhe (U.S. Navy, Retired) states that the Soviet sea strategy is to use cruise missiles in a brief, massive, coordinated, surprise strike. This strike strategy is designed to gain the initiative in the first salvo and then to maintain that advantage. Captain Ruhe reports that a 90-sec response is their goal for coordinated strike timing.

Recent Arab-Israeli conflicts and the Indo-Pakistani War of 1971 are our only sources of information on tactical experience in the use of cruise missiles. The importance of advanced warning, however, was conveniently demonstrated in the Arab-Israeli War of October 1973. In that action, the Israelis were made aware of missile launchings from Arab patrol boats in sufficient time to optimize their own elec-

[1] Ruhe, W. J., "Cruise Missile: The Ship Killer," United States Naval Institute Proceedings, June 1976.

tronic warfare and maneuvering tactics. They were able to prevent hits even though 55 Styx cruise missiles were fired in one engagement.[1] RPV's could be used to keep Soviet ships and aircraft under surveillance and give our forces the time needed to defend against a surprise strike and to provide targeting information for counterattacks by the Harpoon or Tomahawk missile.

MANNED AIRCRAFT APPLICATION

The Navy's manned aircraft operational capability can be extended to smaller aviation-capable ships, thus greatly expanding naval air support capability. This is also prompted by the Soviet cruise missile threat alluded to earlier. Since all Soviet cruise missiles have very large warheads, Captain Ruhe[1] reports that their main purpose is to destroy our capital ships by brute force and to achieve absolute certainty of destruction when the opportunity is presented to attack our carriers.[1] The capability to disperse our carrier aircraft in such an event could counter this Soviet strategy.

The U.S. Navy currently has 315 ships with aviation capability (302/helicopter, 13/aircraft), and 215 of them have hanger space for helicopters. To take advantage of this additional deck space, the Navy can utilize new aircraft with VSTOL capability. Two major vehicle configurations are of importance, a general purpose subsonic configuration and a supersonic fighter/attack configuration. These aircraft will be required to have vertical launch and recovery capability to takeoff and land without catapult assist or arresting gear. In fact, that requirement will govern the designs of these new manned aircraft.

THE VATOL CONCEPT

Over three years ago, the launch and recovery problem (then associated only with RPV's) was investigated at DTNSRDC. Vertical attitude takeoff and landing (VATOL) was found to offer several unique advantages over the other approaches to the problem of launching and recovering aircraft including RPV's. (This can be especially true for supersonic fighter aircraft that have higher thrust to weight ratios). In this attitude the RPV can attach itself to a vertical grid (Figure 1) after docking at the edge of the ship where engine exhaust is overboard and

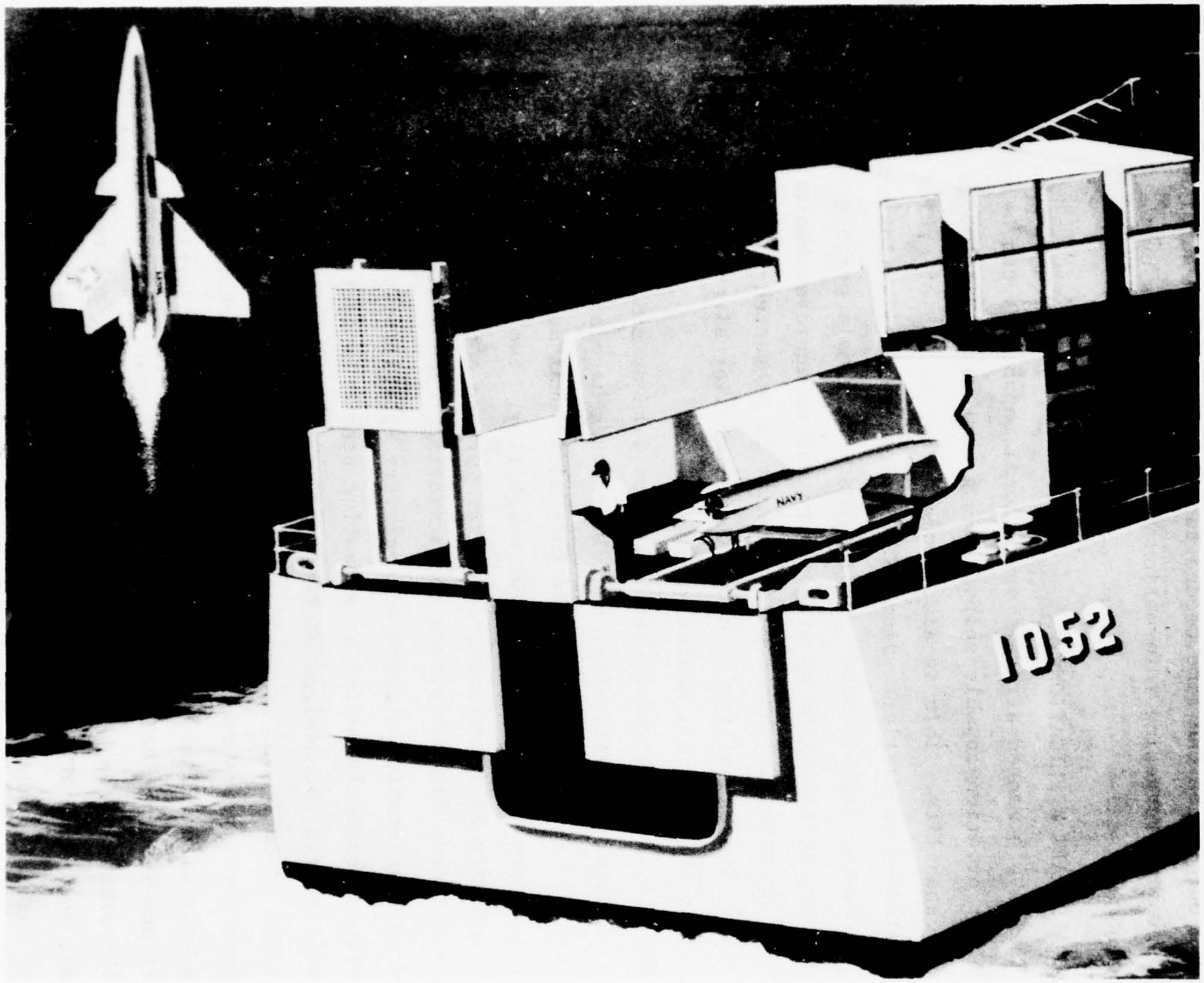

Figure 1 - VATOL RPV Operating from KNOX Class Destroyer (Artist's Concept)

does not have an impact on deck space or crew (as is the case with horizontal attitude VTOL aircraft, i.e., Harrier). The RPV would deploy a harpoon type probe to engage and dock to the grid. A transportable trailer houses the RPV and recovery grids and is self supporting except for external power and fuel.

For a manned aircraft the same advantages apply (Figure 2). In case of sudden loss of thrust while approaching the ship, the pilot can eject and the aircraft will fall clear of the ship, thereby further increasing ship operational safety. Deck space for refurbishment can also be reduced by using space at the edge of the deck.

The vertical attitude configuration is a cheaper design because it will not require new engine development. Existing engines can be utilized since only the engine exhaust plume requires vectoring. Only minor engine modifications would be needed to allow vertical attitude flight in most cases, and available engine bleed air can be used for roll and thrust control. In contrast, horizontal attitude configurations involve expensive new engine development (dedicated engine designs such as the PEGASUS used on the Harrier) or additional lift engines.

This vertical concept was first developed by the Ryan Aeronautical Company nearly 20 years ago. In hover, their design (the X-13 Vertijet, Figure 3) used a swiveled nozzle at the engine exhaust for pitch and yaw control and a jet reaction control system located outboard on the wing for roll control. Test pilots Girard and Everett successfully demonstrated vertical takeoff and transition to horizontal flight and also transition from the horizontal flight back to a vertical attitude for landing. They reported encountering surprisingly few problems.[2] The following conclusions are drawn from a review of several technical papers which reported their experiences:

1. Attitude and altitude control were easily achieved during vertical attitude approach and hover.
2. Hover maneuverability was good, even during intricate maneuvers in winds up to 35 knots and from any direction.

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[2]Girard, P. F. and W. L. Everett, "A Test Pilot Report on the X-13 Vertijet and VZ-3RY Vertiplane." Annals of the New York Academy of Sciences, Vol 107, Art. 1, (25 Mar 1963)

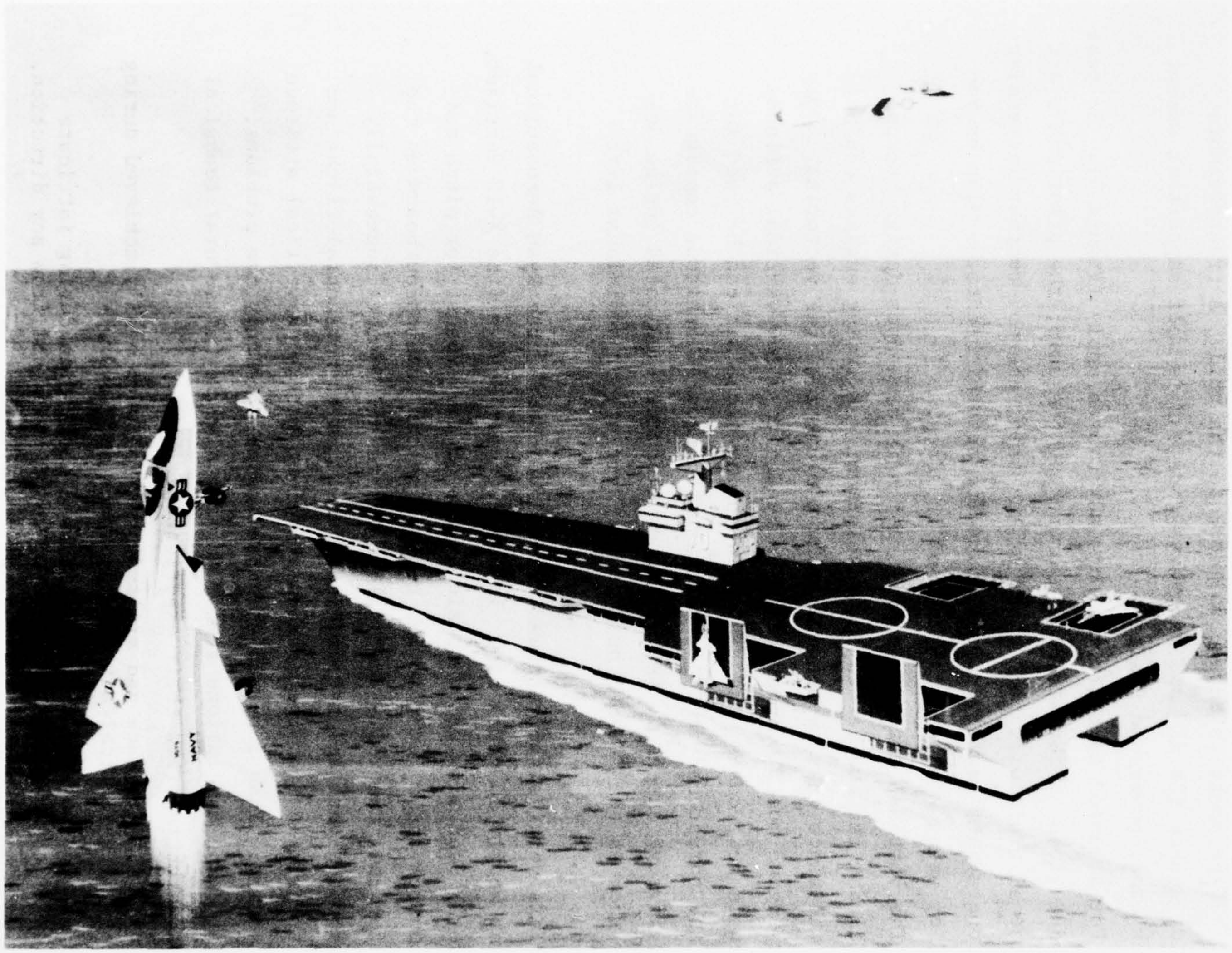

Figure 2 - Manned VATOL Fighter Operating from Vertical Support Ship

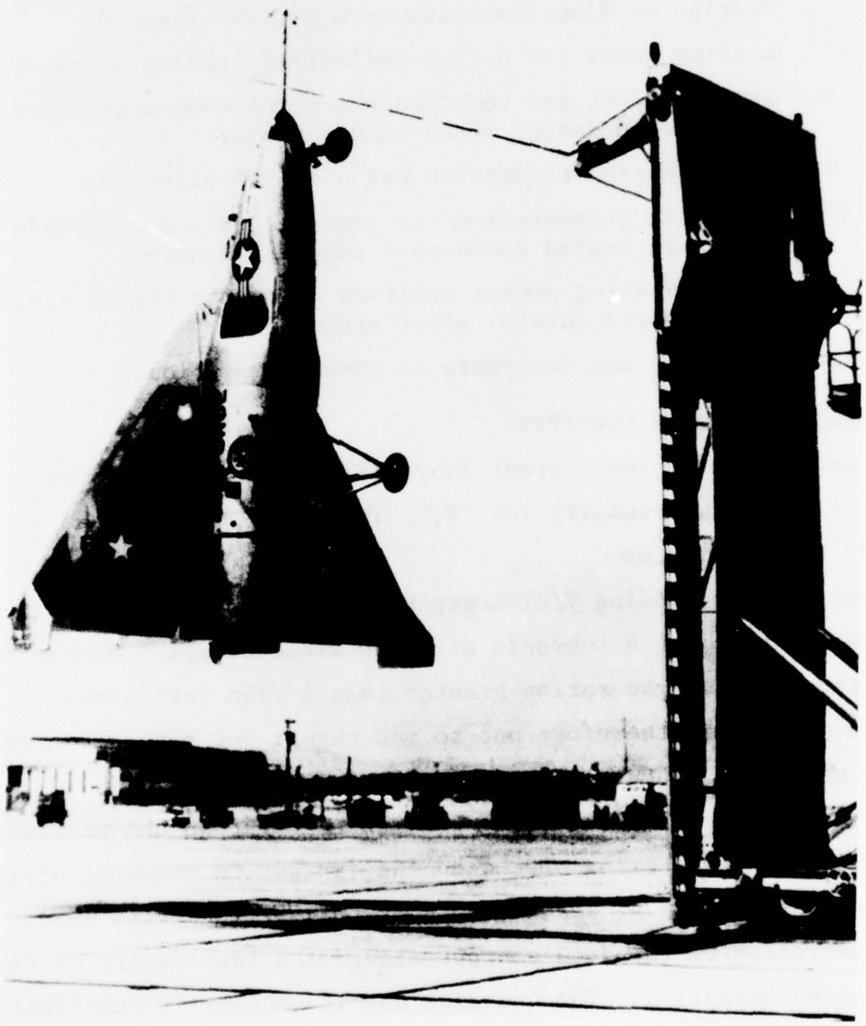

Figure 3 - Ryan X-13 Vertijet

3. A tilting seat was required to aid visibility and to prevent disorientation.
4. Lack of direct forward visibility in landing was not a serious problem.
5. No landing signal officer was required during landing.
6. Vertigo or disorientation were not experienced.
7. Landing loads for a true tailsitter landing averaged 1.15 g's.
8. Strong buffet and unorthodox control characteristics were encountered during transition to hover.
9. Buffet during transition was a useful pilot cue.
10. Stability augmentation was required to aid transition and to cancel engine gyroscopic couples in hover.
11. Thrust setting versus attitude angle was highly nonlinear and required careful pilot attention.
12. High drag was desirable to speed transition.

VATOL COMPARED TO OTHER CONCEPTS

The motivation behind a great many V/STOL concepts has been that elusive goal: minimum penalty for "V." The quest is more than academic for a Navy V/STOL fighter.

In one respect, adding V/STOL capability to a supersonic fighter is less demanding than for a subsonic airplane since superior combat agility dictates thrust to weight ratios greater than 1 even for current fighters. The design problem is therefore not to add thrust but rather to make more effective use of the thrust already available.

The VATOL approach changes the problem rather than the airplane. Small angle thrust vectoring of the engine exhaust in vertical attitude hover is a control mode at least as old as the V-2 rocket of 1944. The 1956 demonstration of the X-13 concept proved the feasibility of VATOL for land-based operation. The question now is whether it constitutes a desirable approach for shipboard basing.

First, consider the performance of the VATOL concept in relation to other candidates for use with a twin engine V/STOL fighter, independent studies of the performance of four fighter-attack concepts, all sized for the same mission, were made by the Vought Corporation:

Vertical Attitude Takeoff and Landing

Lift Plus Lift Cruise

Lift Fans

Ejector Design

The VATOL and lift plus lift/cruise designs were equal in size and both were lighter than the lift fan and ejector airplanes. The VATOL concept, however, exhibited better acceleration and combat ceiling than did the lift plus lift/cruise design. For equal combat and mission performance, the VATOL design was 11 percent lighter than lift plus lift/cruise and could make a vertical landing with one engine out. Other VATOL advantages included low susceptibility to exhaust gas reingestion or impingement on the airframe, no appreciable suckdown problem, availability of thrust vectoring for control in conventional flight, elimination of gas impingement on deck surfaces, and the possibility of operating from small ships without the need for helicopter platforms.

Because of the advantages VATOL offers for RPV's and Navy fighter aircraft, DTNSRDC initiated an in-house effort to design and develop a small (less than 600 lb) demonstration vehicle. A vehicle of this size can utilize existing Navy missile and target drone hardware to reduce costs and still be large enough to allow flight test investigations of vertical attitude docking on a ship underway. This will allow an assessment of the possible problems of landing and takeoff in the air turbulence generated by the ship superstructure. Also, the demonstration vehicle can be used later in the program to study problems associated with ship motion. This delta wing configuration can easily meet the supersonic flight required for manned V/STOL fighter aircraft.

DTNSRDC DEMONSTRATION VATOL VEHICLE XBQM-108A

GENERAL DESCRIPTION

The demonstration vehicle (Figure 4) incorporated a delta wing similar to the Ryan Vertijet. Location of the power plant at the rear of the aircraft will move the cg further aft but will cause no problem because the delta wing exhibits an aft center of pressure.

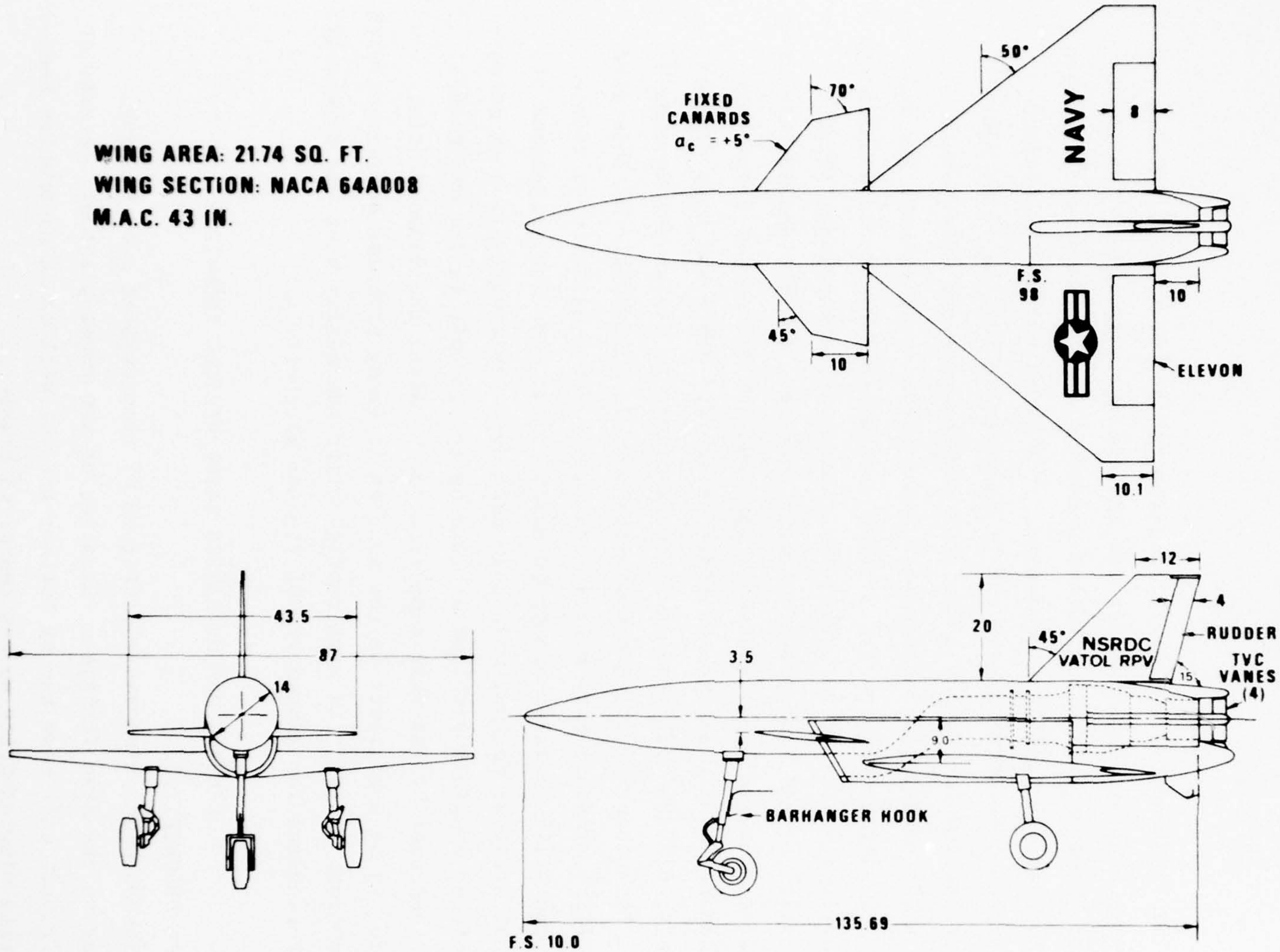

Figure 4 - Details of the DTNSRDC Demonstration Vehicle

A close-coupled canard (fixed for this demonstration) is employed to extend maximum lift (over 50 percent). This increased lift aids the transition from horizontal to vertical flight and also reduces conventional horizontal runway landing speed.

A single vertical tail is used for directional stability during horizontal flight. Elevons on the wing and a rudder on the vertical tail are used for horizontal flight control. The wing, canard, and vertical tail are constructed of aluminum stringers and plates and covered with high-density styrofoam bonded to layers of fiberglass. The elevons and rudder are made of mahogany.

During the initial sizing and design phase, a survey of available engines indicated that the Teledyne CAE XJ402 (used earlier in the design phase of the Harpoon missile) was an attractive engine candidate. Not only can it generate 660 lb (uninstalled, sea level) of static thrust but it also possesses an engine-mounted dc alternator. (The YJ402 Harpoon does not have an alternator; it was used during the tethered hover test phase with electric power supplied from ground support equipment.)

Following selection of this engine for the demonstration vehicle, an aft fuselage structure of aluminum frames and stringers was designed around it. The structure is covered with aluminum panels and uses a steel ring to support the five engine support pins at a single station.

A fiberglass inlet duct supplies air to the engine. It is an S-shaped duct with a "kidney"-shaped entrance underslung beneath the forward fuselage. The exit shape is circular at the engine inlet attachment. A rubber gasket cushions and seals the engine inlet interface. The inlet duct area ratio is large (1.10) to reduce pressure and distortion losses of the inlet in hover. The inlet lip is relatively large to minimize flow separation during hover. The aft engine compartment is cooled at the engine tail pipe by an air ejector designed for maximum pumping with no loss in thrust. Vent openings on the side of the fuselage supply air to the ejector.

The nose cone and forward fuel tank of the MQM-74A target drone constitute the forward section of the fuselage. This structure houses the command and control receiver and decoder for the target drone.

The Harpoon midcourse guidance unit (MGU) is used to stabilize the demonstration vehicle in flight. The MGU is an integrated package designed to provide guidance and control from takeoff to terminal guidance takeover. It serves as both an autopilot and an inertial navigator by means of an attitude reference assembly (ARA) in a strapdown inertial sensor configuration, a digital computer autopilot (DCA), and a self-contained power supply. The assemblies are packaged within a 12-in. diameter by 6-in.-long cylinder weighing 25 lb.

The MGU sends control signals to the elevon and rudder rotary electromechanical actuators via servoamplifiers for horizontal flight control. For control in the vertical attitude (hover), signals are sent to linear electromechanical actuators that drive four high-temperature steel (Hastelloy X) vanes located in the engine exhaust (Figure 5). The use of vanes simplifies the hover control system design compared to the swiveled nozzle used on the Ryan Vertijet. In hover the engine is operating near maximum thrust and this produces high-velocity jet exhaust. Vanes operating in this jet produce sufficient forces to provide control in pitch, roll, and yaw.

The Harpoon radar altimeter is used to sense altitude in horizontal flight as well as in hover. Radar transmitting and receiving antennas are located flush on the lower wing surface in front of the elevons during horizontal flight (one on each wing). As the RPV transits to a vertical attitude, the antennas are spring loaded and hinged, allowing rotation through 90 deg so that altitude can be measured during hover.

A fixed tricycle landing gear (from the BD-5J aircraft) is attached to the wing and nose of the demonstration vehicle to provide conventional horizontal takeoff and landing capability. A hook is welded to the nose gear to allow vertical docking to a cable attached to a mobile trailer/erector. A hydraulic brake system is employed on the main landing gear and provides braking during landing rollout.

The MQM-74A recovery chute has been retained. This will allow emergency recovery capability during future flight tests. A drag chute is also installed in the fuselage tail cone to assist with braking during landing rollout. The vehicle configuration is summarized in Table 1.

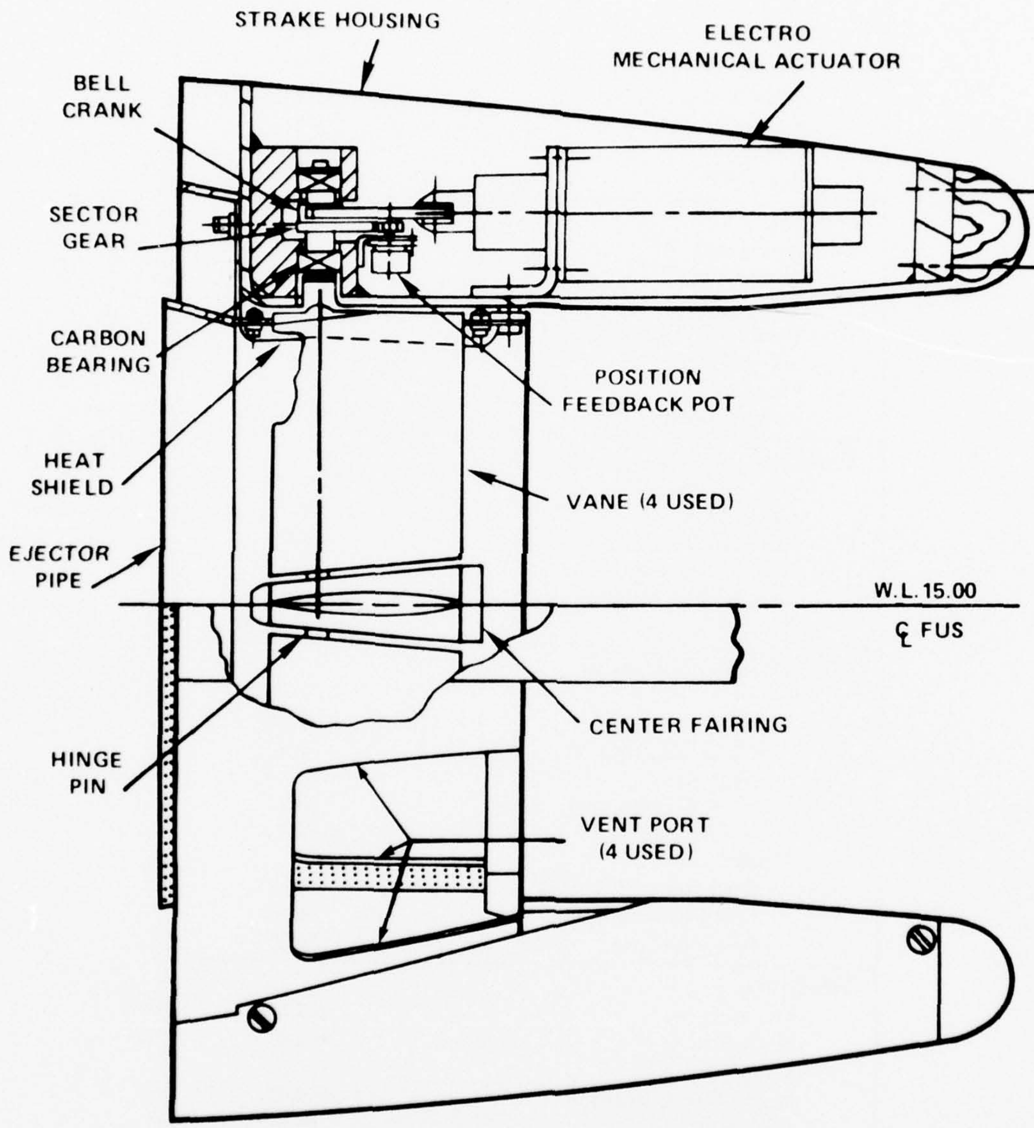

Figure 5 - Internal Vane Assembly for the Demonstration Vehicle

TABLE 1 - CONFIGURATION DATA FOR VATOL RPV DEMONSTRATION VEHICLE

WING	
Area (total), ft^2	21.74
Aspect Ratio	2.42
Taper Ratio	0.16
Span, in.	87.0
Sweepback at LE, deg	50.0
Dihedral, deg	2.8
Incidence, deg	+2.0
MAC, in.	42.2
Airfoil Section	NACA 64A008
CANARD	
Area (total), ft^2	5.07
Aspect Ratio	0.26
Span, in.	43.5
Sweepback at LE, deg	45/70
Dihedral, deg	0
Incidence	+5
Airfoil Section	NACA 0006
VERTICAL TAIL	
Area (exposed) ft^2	2.69
Aspect Ratio	1.032
Taper Ratio	0.45
Span, in. (exposed)	20.0
Sweepback at LE, deg	45.0
Airfoil Section	NACA 0006
CONTROL SURFACES	
Elevon	
Span, in.	25.625
Chord (constant), in.	8.3
Deflection	
T.E. down, deg	10.0
T.E. up, deg	40.0
Rudder	
Span. in.	19.125
Chord (constant), in.	4.0
Deflection, deg	± 30.0
WEIGHTS	
Structure, lb	203.7
Propulsion, lb	105.0
Equipment, lb	159.9
Weight Empty (total), lb	448.62
Fuel (JP-4), lb	94.3
Takeoff Gross Weight, lb	562.9
Touchdown Weight, lb	477.4
CG AND INERTIAS	
At takeoff, F.S., W.L.	89.75, 11.3
At landing, F.S., W.L.	86.55, 11.67
Moments of Inertia at takeoff (slug-ft^2), I_x, I_y, I_z	113, 17.64, 108
Moments of Inertia at landing (slug-ft^2), I_x, I_y, I_z	110, 17.2, 105

AERODYNAMIC CHARACTERISTICS IN HOVER

To determine the aerodynamic characteristics in hover, a 30-percent scale model of the demonstration vehicle was designed and evaluated in the DTNSRDC 8- by 10-ft subsonic tunnel. The model was rotated in the pitch plane up to 45-deg angle of attack α to define the vehicle characteristics for horizontal flight. The vehicle was rotated 90 deg in roll and the support strut was yawed through 90 deg to obtain data for hover flight.

The horizontal flight data were obtained at a dynamic pressure of 60 psf (153 mph) and hover data were obtained at 10 psf (63 mph). The model was rolled through 180 deg to determine the effects of various wind directions on vehicle characteristics, especially rolling moment. The horizontal flight aerodynamic data are presented in Reference 3.

In the vertical attitude, the maximum rolling moment coefficient (C_ℓ = -0.138) occurred at a roll angle of 170 deg as measured from a plane through the RPV centerline including the vertical tail. The maximum pitching moment coefficient at liftoff weight (C_m = 0.148) occurred at a roll angle of 140 deg. The maximum normal force coefficient C_N was 1.84 and side force coefficient C_Y was 0.87; these values occurred at roll angles of 0 and 120 deg, respectively.

The forces and moments these coefficients generate are a function of the wind speed at takeoff and landing. For example, at 30 knots the wind dynamic pressure q was only 3.0 psf and the resulting maximum forces and moments on the RPV were as follows (at the center of gravity; e.g., for takeoff):

Rolling moment	=	27.6 ft-lb
Pitching moment	=	29.6 ft-lb
Yawing moment	=	18.4 ft-lb
Normal force	=	119.6 lb
Side force	=	56.6 lb

---

[3]Eilertson, W.H., "Vertical Attitude Takeoff and Landing Remotely Piloted Demonstration Vehicle," Society of Automotive Engineers, National Aerospace Engineering and Manufacturing Meeting, Culver City, Los Angeles, 17-20 November 1976, Paper 751103.

These forces and moments must be within the power capability of the jet vane control. Of course side forces and moments are almost zero in calm winds and rolling moment is also small. Pitching moments are still large because of thrust/cg offset and moments generated by the inlet air flow. These moments reach 3000 in-lb nose down at takeoff thrust. A total force of 621 lb is required on the two pitch vanes to trim this moment. A pitch vane angle of attack of 10.1 deg is required to generate this force. Since the vane throw is limited to ± 15 deg, the "zero" pitch vane position was set at -10 deg (trailing edge up) during the hover flight tests. A drag chute was employed to ensure adequate roll control during transition.*

JET VANE PERFORMANCE

Jet vanes are used in the engine exhaust for hover control (Figure 5) primarily for design simplicity and lower cost. The vanes were originally sized to provide recommended angular accelerations in pitch, roll, and yaw based on handling quality criteria specified for V/STOL aircraft in MIL-F-83300. These accelerations are:

Pitch: 0.5 rad/sec^2

Roll: 3.0 rad/sec^2

Yaw: 0.6 rad/sec^2

The vanes were sized to generate the pitch and yaw levels of acceleration at small vane deflection angles. The resulting vane chord is 2.5 in. The two horizontal vanes have been designed to extend to a vertical insert that is supported by the two vertical vanes (Figure 5). This increases horizontal vanes effecitveness to help trim moments generated by thrust/cg offset and inlet air flow.

---

*The Ryan Vertijet had a swiveled nozzle at the engine exhaust for pitch and yaw control and engine throttling for axial control. For roll control, air was bled off the engine compressor to reaction jets near the wing tip. Roll control was marginal on the X-13 in transition due to low reaction jet thrust; this thrust was low because the low engine rpm generated low thrust levels required in the initial phase of transition to prevent altitude zooming.[2] It was suggested that a drag brake could be used to reduce forward flight speed and require higher thrust levels and engine rpm to eliminate this problem. The DTNSRDC demonstration model employs a drag chute for this purpose.

PRELIMINARY TESTS

Early experiments involving engine operations were performed at the Naval Weapons Center (NWC), China Lake, to verify vane assembly design. The vanes were mounted in the engine exhaust about 9 in. aft of the engine tail pipe. The pitch vanes did not extend to the centerline and the center fairing was not present. One vane was mounted to a balance (supplied by DTNSRDC) and forces and moments on the vane were recorded at different thrust levels.[3] The vane was rotated through an angle of attack range of -20 to +20 deg. The lift force per degree (L_δ) generated by the vane was measured for engine thrust ranging from 200 to 412 lb. This was the range measured by a load cell during engine operation. For an extrapolated thrust level of 560 lb, vane lift was only 1.09 lb per degree of vane deflection.

Because the value of lift generated by the vane during these tests was lower than earlier estimates, an effort was initiated to determine the exhaust velocity profile in the vicinity of the vane by utilizing data from Sandia Corporation.*

The engine core velocity V_e in the exhaust is based on the dynamic pressure of the flow q_e. For a liftoff thrust of 560 lb, q_e = 10.7 psi = 1541 psf (supplied by Teledyne CAE). Exhaust velocity is:

$$V_e = \sqrt{\frac{q_e}{1/2\ \rho_e}} = 1938.56 \text{ fps, where exhaust density } \rho_e \text{ is } 0.00082$$

$lb\text{-}sec^2/ft^4$.

---

*During their 1963 tests of a free jet at Mach 0.7 to 1.96, Sandia personnel conducted radial static and pitot pressure surveys at various stations downstream.[4] Velocity profiles between the high-velocity flow and surrounding air were calculated from the pressure data. A constant total temperature across this mixing region was assumed. As predicted by theory, the width of the mixing region between the engine high-velocity flow and surrounding still air varied linearly with axial distance at all Mach numbers and grew appreciably downstream from the engines exhaust pipe. There was also no discernable effect of compressibility on the shape of the velocity provile. This resulted in a shrinkage of the high exhaust velocity flow until the diameter at the vane was only about 3 in. compared to the engine exit diameter of 6 in.

[4]Reed, J.F. and R.C. Maydew, "Turbulent Mixing of Axisymmetric Compressible Jets (in the Half-Jet Region) with Quiescent Air," Sandia Corporation Report SC-4764 (RR), (Mar 1963).

From the Sandia data, the velocity distribution at the vane location was calculated for a core velocity (V_e) = 1938 fps and plotted versus Y (Figure 6) for both the internal and externally mounted vanes. Y is the radial distance away from the engine centerline.

For the velocity distribution shown in Figure 6 vane lift is also a function of the dynamic pressure variation in engine exhaust. The dynamic pressure q_e in the region of constant velocity is a function of the exhaust velocity as shown by the equation

$$q_e = 1/2 \rho_e V_e^2$$

Subsequently q varied as the velocity dropped off in the mixing region between the engine core flow and the surrounding still air. Density in the mixing region also varied from 0.00082 lb-sec^2/ft^4 in the high velocity flow to 0.00238 lb-sec^2/ft^4 for still air at sea level. The average value of q over the vane was determined to be 1135 psf.

The vane lift per degree (L_δ) for this average value of q is $L_\delta = C_{L_\delta} q_{AVG} s_v$ where C_{L_δ} is the vane lift coefficient slope. C_{L_δ} was estimated to be 0.024 and vane area (s_v) to be 0.045 ft^2. Therefore L_δ = 0.024 (1135) 0.045 = 1.23 lb/deg. This estimated lift force compares favorably to the extrapolated test data from the China Lake experiments, namely 1.09 lb/deg.

Vane performance was improved in two ways:

1. The effective aspect ratio of the vane was increased by extending the two horizontal vanes to the centerline. This not only increased the vane aspect ratio but also increased its area to 0.052. It was estimated that the horizontal vane could produce a lift up to a value of L_δ equal to 2.35 lb/deg. A fairing that extends between the top and bottom vanes acts as an endplate for the left and right horizontal vanes.
2. The vane assembly was reconstructed with the vanes inside the cooling air ejector pipe and near the engine exhaust. This location placed the vanes where they would "see" more of the engine high exhaust velocity before mising took place. The internal vane velocity and q distribution estimates were generated and plotted.[3] It was determined from these distributions that q_{AVG} increased to 1355 psf. With

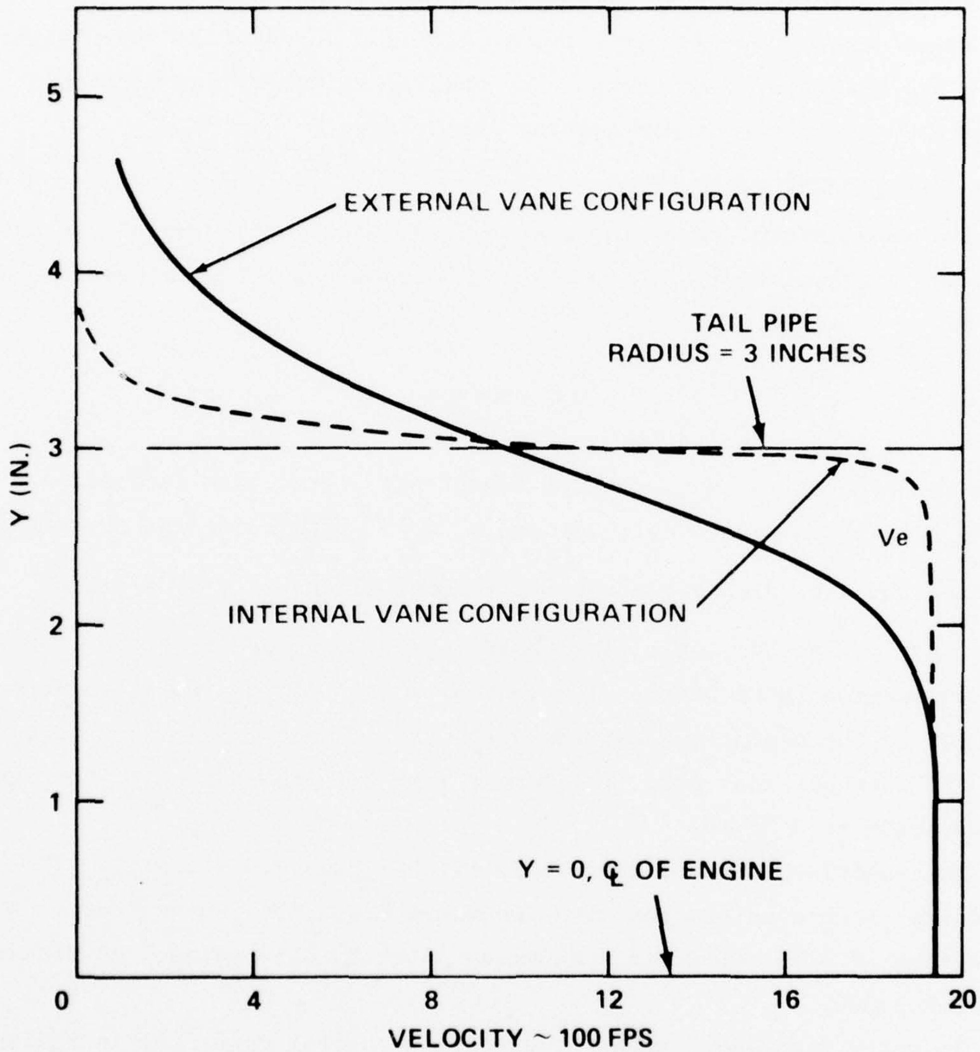

Figure 6 - Vane Velocity Distribution for the Demonstration Vehicle (As generated from Sandia data[4])

C_{L_δ} 0.04 for the horizontal vanes, L_δ increased to 2.82 lb/deg. The vertical vane was the same as before (s_V = 0.04 ft^2) but the higher q_{AVG} resulted in a value of L_δ = 1.46 lb/deg.

These values for vane performance provided successful hover flight during the tethered hover tests. The control accelerations were then determined to further assess control capability.

VANE CONTROL POWER ESTIMATE

The vane control power for the internal vane configuration was estimated for a takeoff weight of 560 lb. The vane angular acceleration control power in pitch $\ddot{\alpha}$ is:

$$\ddot{\alpha} = \frac{\partial M}{\partial \delta_v} \delta_v \cdot \frac{1}{I_x}, \text{ rad/sec}^2$$

where for each pitch vane, control moment per degree vane deflection ($\partial M/\partial \delta_v$) is 17.38 ft-lb/deg (= C_{L_δ} x_v q_e s_v). This value was determined by using the estimated pitch vane lift curve slope C_{L_δ} = 0.04 deg of pitch vane deflection for a vane chord c_v = 2.5 in. and 6 percent thick airfoil section (NACA 0006). The vane area (s_v) of the two pitch vanes affected by the engine exhaust was 0.104 ft^2. The average value of q_e over the vane was 1355 psf. The moment arm (x_v) from the cg to the vane was approximately 37 in.

The vehicle moment of inertia in pitch I_x was 113 slug-ft^2. The resulting pitch acceleration with two vanes was 0.154 rad/sec^2/deg. A deflection of 3.25 deg would accelerate pitch by 0.5 rad/sec^2 as required by MIL-F-83300.

In roll, the vane angular acceleration control power ($\ddot{\phi}$) in radians per $second^2$ is:

$$\ddot{\phi} = \frac{\partial L}{\partial \delta} \delta_v, \frac{1}{I_y}$$

Roll control moment per degree deflection ($\partial L/\partial \delta_v$) was low (1.13 ft-lb/deg) for the four vanes since the vane moment arm in roll ℓm was relatively short, only 1.50 in. for the horizontal vanes and 1.75 in. for the vertical vanes. The pitch vanes contributed 0.70 ft-lb/deg compared to 0.425

ft-lb/deg for the smaller yaw vanes. The low moment of inertia in roll (I_y = 17.64 slug-ft^2) helped to offset the short vane roll moment arm. The resulting roll acceleration was low, only 0.64 rad/sec^2 per degree of vane deflection. However, this is sufficient for control of the vehicle in low winds or at small roll angles in high winds.

In yaw, the vane angular acceleration control power ($\ddot{\beta}$) in radians per second was:

$$\ddot{\beta} = \frac{\partial N}{\partial \delta_v} \delta_v \cdot \frac{1}{I_z}$$

For one vane, yaw control moment per degree deflection ($\partial N/\partial \delta_v$) was less than the pitch vane (4.50 compared to 17.38 ft-lb/deg) because of the smaller vane area and lower value of $C_{L_{\delta_v}}$. The vane moment arm in yaw was the same as in pitch (37 in.). The vehicle moment of inertia in yaw was 108 slug-ft^2. Vane angular acceleration was therefore 0.083 rad/sec^2 per degree of vane deflection for two vanes; 7.23 deg deflection will result in an acceleration in yaw of 0.6 rad/sec^2.

Since no test data existed to validate the above estimates on a vane control system mounted behind a jet engine, the two vane designs were evaluated by mounting the vehicle to a cradle and balance.

CRADLE EXPERIMENTS AND RESULTS

To determine the installed jet vane performance, a wooden cradle was constructed to support the demonstration vehicle on a six-component balance (rated at 1000-lb normal force). The cradle was mounted on the trailer/erector, and vertical struts were used to attach the vehicle to the cradle at the main gear wheels and at the fuselage just in front of the inlet (Figure 7). (The nose cone and wheel were removed.) In this manner the vane forces could be translated to the balance which was located near the cg of the demonstration vehicle just below the fuselage. The balance was supported as high as possible above the trailer bed to minimize large nose-down moments generated by jet engines thrust.

In addition to determining the aerodynamics besides measuring the performance of the two jet vane configurations, installed engine thrust and engine speed control response were also measured along with direct

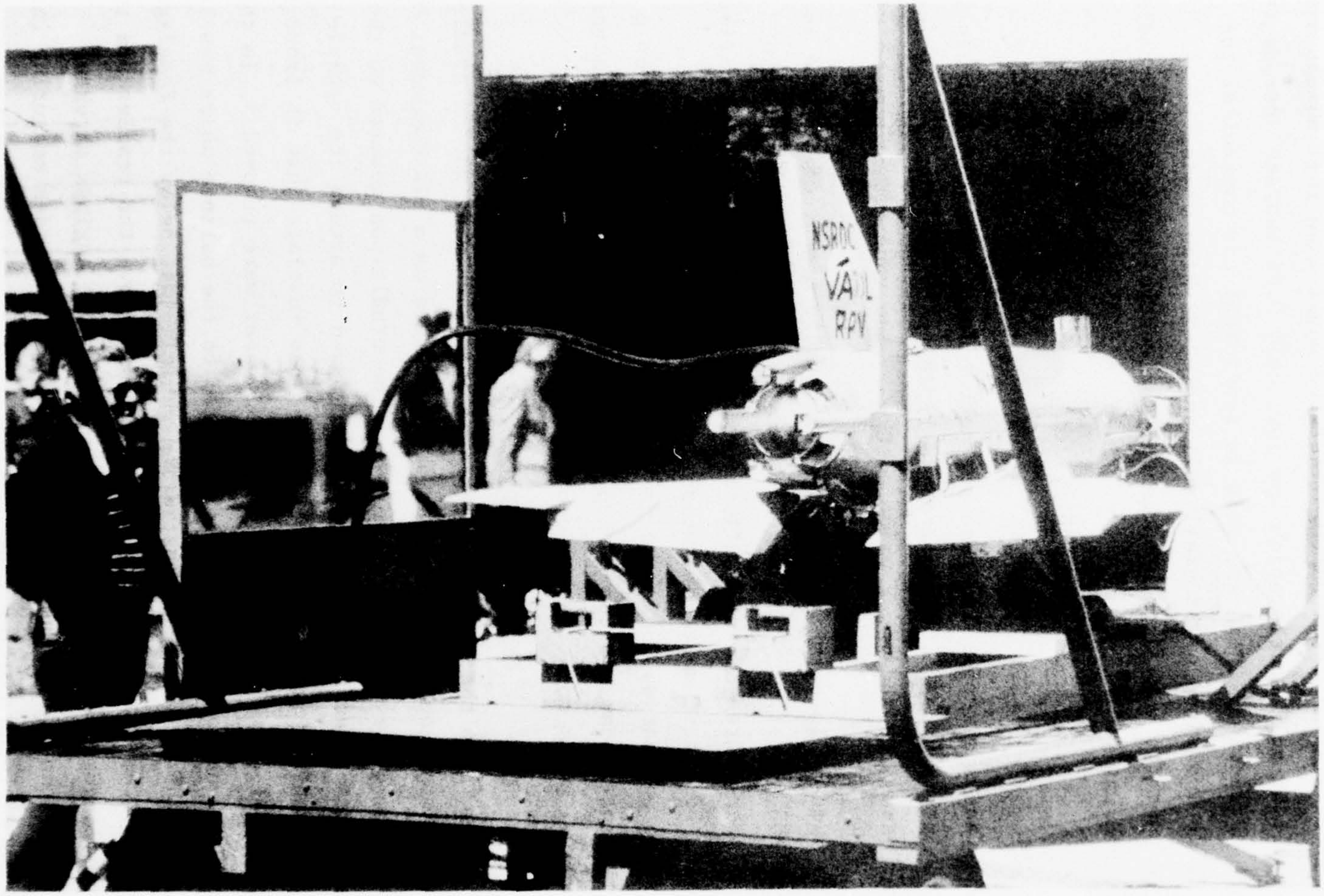

Figure 7 - Cradle Test of Demonstration Vehicle, Run 5 (Internal Vanes)

estimates of the effects of engine air inlet, small engine misalignments, and engine jet exhaust.

A computer program was generated by personnel at the Naval Underwater Systems Center and loaded into the autopilot (MGU) computer on the demonstration vehicle to enable automatic control of the vanes and engine speed. The total program time was 7 min and 21 sec. This greatly enhanced operations, leaving personnel free to observe jet vane motion in the engine exhaust. Engine vibration, exhaust gas temperatures, and inlet temperatures were also monitored.

Five runs were made during April and May of 1976. The first run was hampered by a restricted fuel flow (maximum thrust was only 430 lb). The fuel for the engine (JET A was used) was supplied from a 42-gal barrel adjacent to the test site and a fuel hose that ran about 40 ft. This line (originally 3/8 in. ID) was replaced by a larger hose (5/8 in. ID). The second run was satisfactory and generated data on the external vane configuration. The third test generated data with no vane assembly attached, and the fourth and fifth runs were made with the internal vane configuration attached.

Prior to engine lightoff, the balance readings of the cradle and vehicle weights and moments were zeroed so that the forces and moments measured were those due only to vane deflection, engine thrust, inlet flow, exhaust effects, and small engine misalignments. The data were reduced about a cg at F.S.92.375 in. and a W.L. = 12.5 in. (engine centerline at W.L. = 15.0). Because of engine vibration, the data tended to be scattered and in most cases ten readings were averaged.

EXTERNAL VANE PERFORMANCE

During run 1, Vane 1 (top, vertical) was inoperative due to the failure of the actuators servoamplifier. However, data are available for the one yaw vane that operated.

Figure 8 shows normal force data for a thrust level of 518 lb together with thrust variation is attributable to the variation in drag as the vanes moved through their angle of attack range. Note that the pitch vanes (2 and 4) were offset -10 deg (trailing edge up). As shown in a crossplot (Figure 9), the normal force per degree deflection dropped to

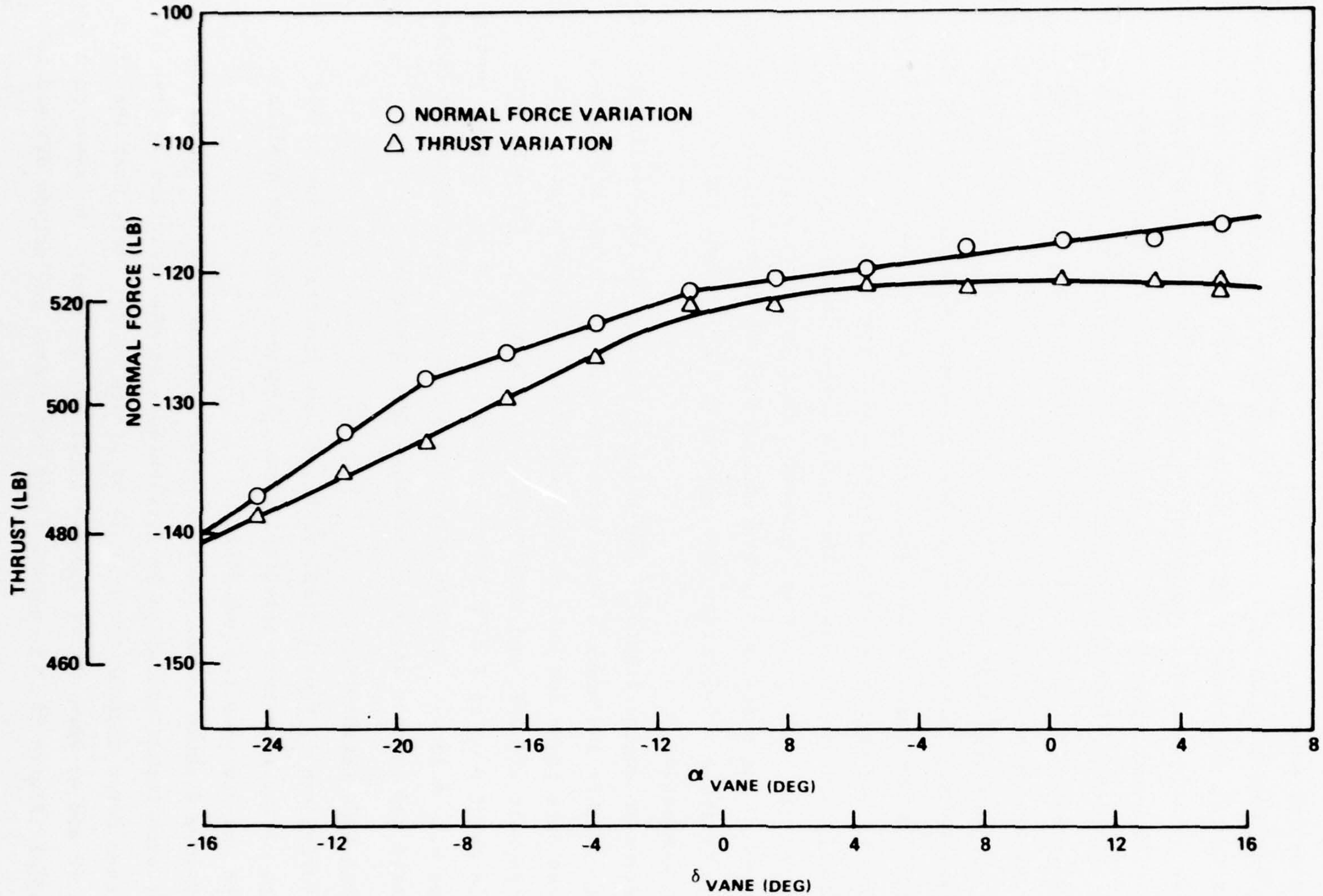

Figure 8 - Normal Force and Thrust Variation (Maximum Thrust Range) for the Demonstration Vehicle

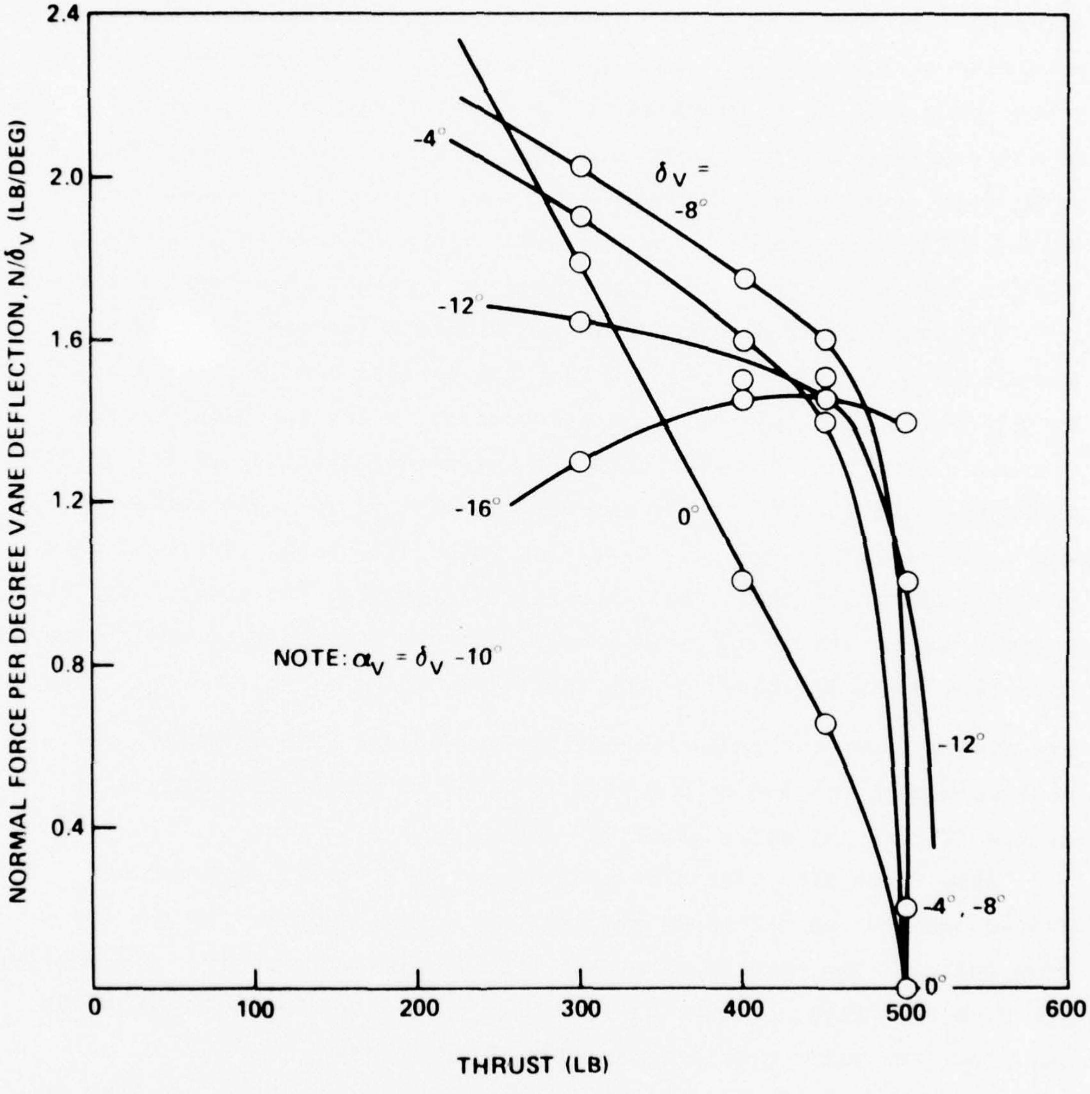

Figure 9 - Drop in Normal Force for Two Pitch Vanes with Increase in Thrust

zero at the high thrust level, apparently because these vanes affected the pressure distribution over their support structure at the rear of the fuselage. No pressures were measured on the aft fuselage but the pitching moment data that were generated indicated that the vanes were effective at high thrust. Note also that the level of normal force was quite large, 140 lb of download at 480 lb of thrust and a vane deflection of -16 deg (Figure 9). Inasmuch as the fully deflected vanes generated only 30 lb, the primary reason for this download was apparently the engine inlet flow (through the S-shaped inlet). Such a download would require nose-up attitude to trim (with the vertical component of thrust).

Pitching moment data are shown in Figure 10 for the three thrust levels employed. Data indicate that the vehicle can be trimmed at all thrust levels, but trim settings occurred at -9 deg for higher thrust levels. The pitching moment data are referenced about cg at F.S.92.375 which is 2.625 in. aft of the takeoff cg. The pitch vane control moment was estimated to be 9.44 ft-lb/deg for each pitch vane. The test data showed a control moment from 10 to 16 ft-lb/deg for two vanes. For the shorter moment arm of the cradle test, the earlier estimate would have been 14.4 ft-lb/deg based on the estimated value of C_{L_δ} and q_e. Thus, the cradle tests confirmed the earlier estimates. The variation of control moment was due to the drop in slope at higher vane angles of attack (Figure 10) above about -10 deg.

Side force data were also generated. Only Vane 3 (bottom) was tested because, as mentioned earlier, the servoamplifier for the top vane failed. The data do show that trim in yaw is possible. The smaller yaw vane side force at the higher thrust levels reached 1 lb/deg which was about the value predicted earlier (1.23 lb/deg).

Yawing moments generated were again for one rudder only. Vane deflecting for trim in yaw actually decreased as thrust increased. The yaw vane control power ranged from 2.5 to 7.5 ft-lb/deg at the higher thrust levels. Earlier it was estimated that one yaw vane would produce 4.90 ft-lb/deg of yaw control moment at a cg 2.625 in. forward of the cradle test reference cg. For the further aft cg tested, the estimated value would have been 4.63 ft-lb/deg.

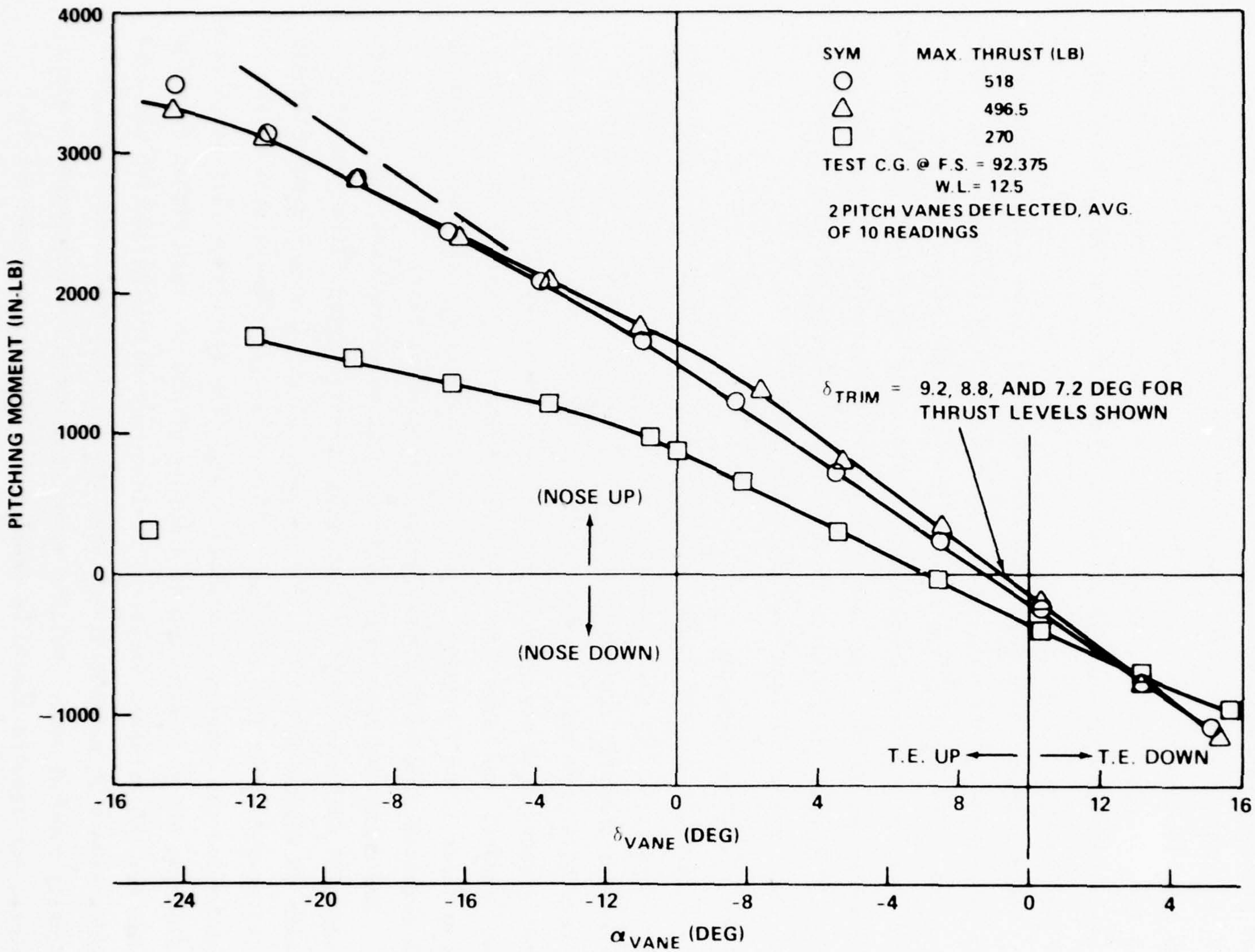

Figure 10 - Pitching Moment of Demonstration Vehicle at Three Thrust Levels

The lower vane measured (2.5 ft-lb/deg) was below the estimated value probably because the engine tail pipe was misaligned slightly (1/8 in.) up and to the right, thus reducing the amount of high velocity flow covering the bottom vane. Had the top rather than the bottom vane been in operation, the yawing moment would have been higher. The test results indicate that control power was higher than estimated at higher vane deflections.

Rolling moment data were generated for only three vanes. Data that were referenced to the balance center showed fairly linear trends. However, data referenced to the cg were too scattered because of the one fixed vane. This was primarily due to the large moment arm of the bottom vane above the balance cg. Attempts to extract meaningful data for roll failed. However, the results from the pitch and yaw analysis indicate that there was sufficient vane power for roll control.

INTERNAL VANE PERFORMANCE

Internally mounted vanes were about 1.2 in. aft of the engine tailpipe (Figure 5). In this location, vane support structure temperatures are higher than for the external vane. Insulation was not employed to protect this structure (as was later done in the hover flight tests) and binding under load occurred on some of the vanes, particularly Vane 1 (top, rudder) and later Vane 4 (left, elevator). Possible contact between Vanes 1 and 2 occurred during the combination angle sweeps although the computer program used was designed to prevent this.

The resulting data were scattered, but an attempt was made to extract meaningful data where one or two vanes operated freely during various phases of engine operation. For example, pitching moment reached levels of 13 ft-lb/deg at 530-lb thrust. This is at least comparable to the results for the externally mounted vanes. The pitch vane lift per degree deflection was 2 lb/deg/vane at a thrust of 530 lb, much higher than the value for the external vanes. Side force per degree deflection was 1.58 lb/deg--about 50 percent higher than the 1 lb/deg generated by the externally mounted vane. Rolling moment data were too scattered to extrapolate, but results should be equal to or better than those for the external vane configuration. Although the internal vane data were in-

sufficient, the trends indicated that this would be the best vane configuration to use in the tethered hover flight tests (after steps were taken to correct high temperature effects by the use of insulation).

ENGINE RESPONSE

Accordingly, during engine operation on the cradle, the engine speed was automatically varied from one level to another. Engine speed response is of interest in modeling the hover control laws. A typical response is shown in Figure 11, and thrust response rate in pounds/second is shown in Figure 12 as a function of thrust. At high thrust levels, the engine response rate dropped to 15 lb/sec. The cradle experiments confirmed the analytical estimates of vane performance. The results were incorporated into a hover flight simulation digital program generated by the Naval Underwater Systems Center (NUSC).

FLIGHT SIMULATION - HOVER FLIGHT PHASE

Prior to the hover flight simulation, available DTNSRDC data on vehicle mass, inertia, and aerodynamic characteristics and jet vane control power were utilized in a stability and control analysis. A digital simulation program was then developed to demonstrate the feasibility of using jet vanes to control the vehicle in hover.[5]

In the simulation program the altitude during hover was maintained by varying engine thrust (via changes in engine speed or rpm). The engine controller model simulated engine rpm from 70 to 100 percent on a first order lag with a 0.35-sec time constant. The thrust was then calculated for two linear segments based on rpm versus the commanded rpm (designated rpmC): Thus rpm = (rpmC-rpm)/0.35 and thrust = 0.0313 (rpm) - 724 for rpm from 28,550 to 36,650 and equal to 0.0447 (rpm) - 1204 for rpm from 36,650 to 40,800. This yields a minimum thrust of 169 lb at 28,550 rpm and a maximum thrust of 621 lb at 40,800 rpm. At the current level of 98 percent rpm (39,984) (limit by hardware constraints) the maximum thrust is 584 lb.

The engine controller model calculates the engine speed command required to hold altitude (rpmC) as the integral of the speed command rate:

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[5]"Simulation Analysis of the Stability and Control of a DTNSRDC Vertical Takeoff and Landing RPV," Naval Underwater System Center TM 3644-4328-76, (Dec 1976)

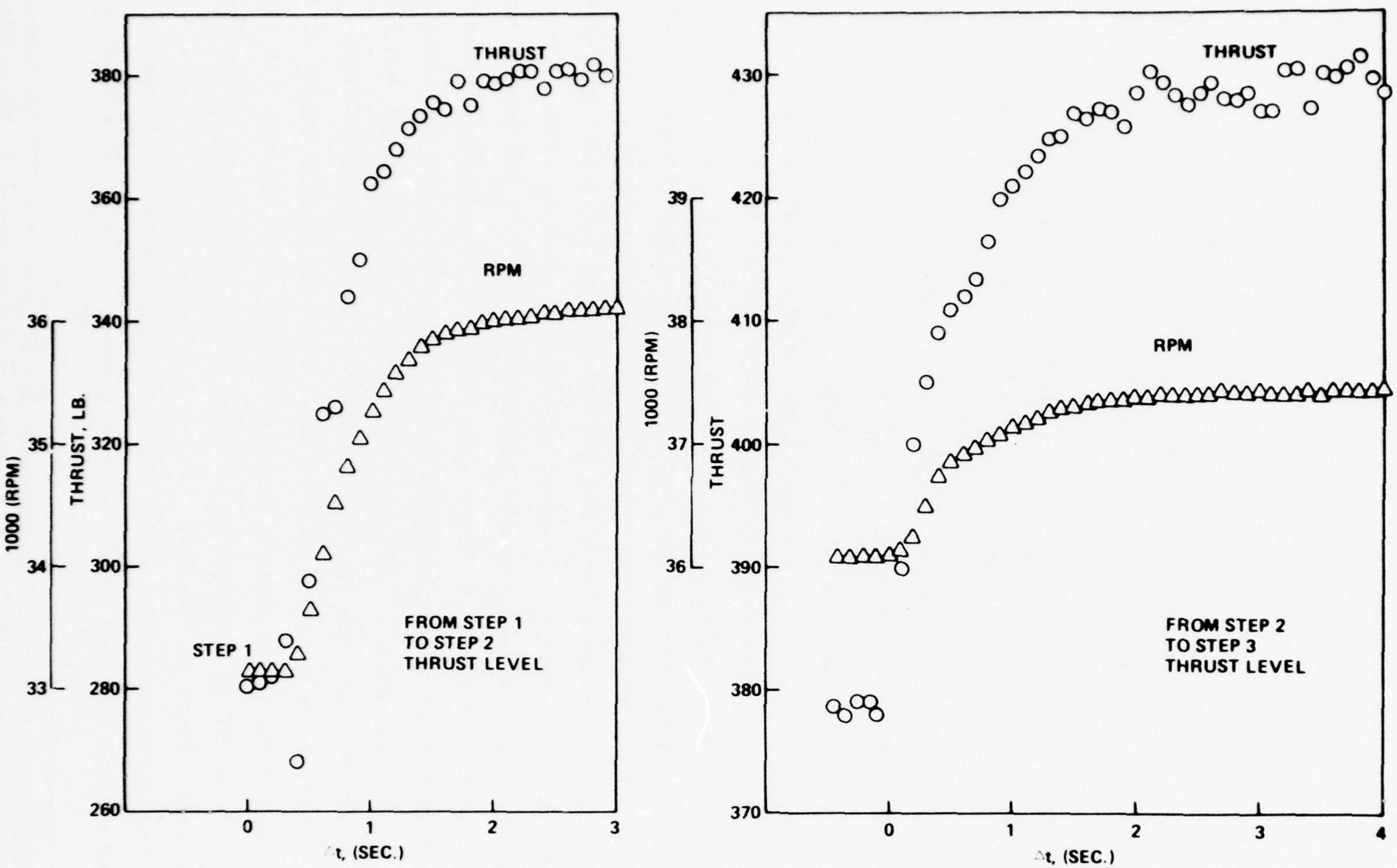

Figure 11 - Engine Speed Response

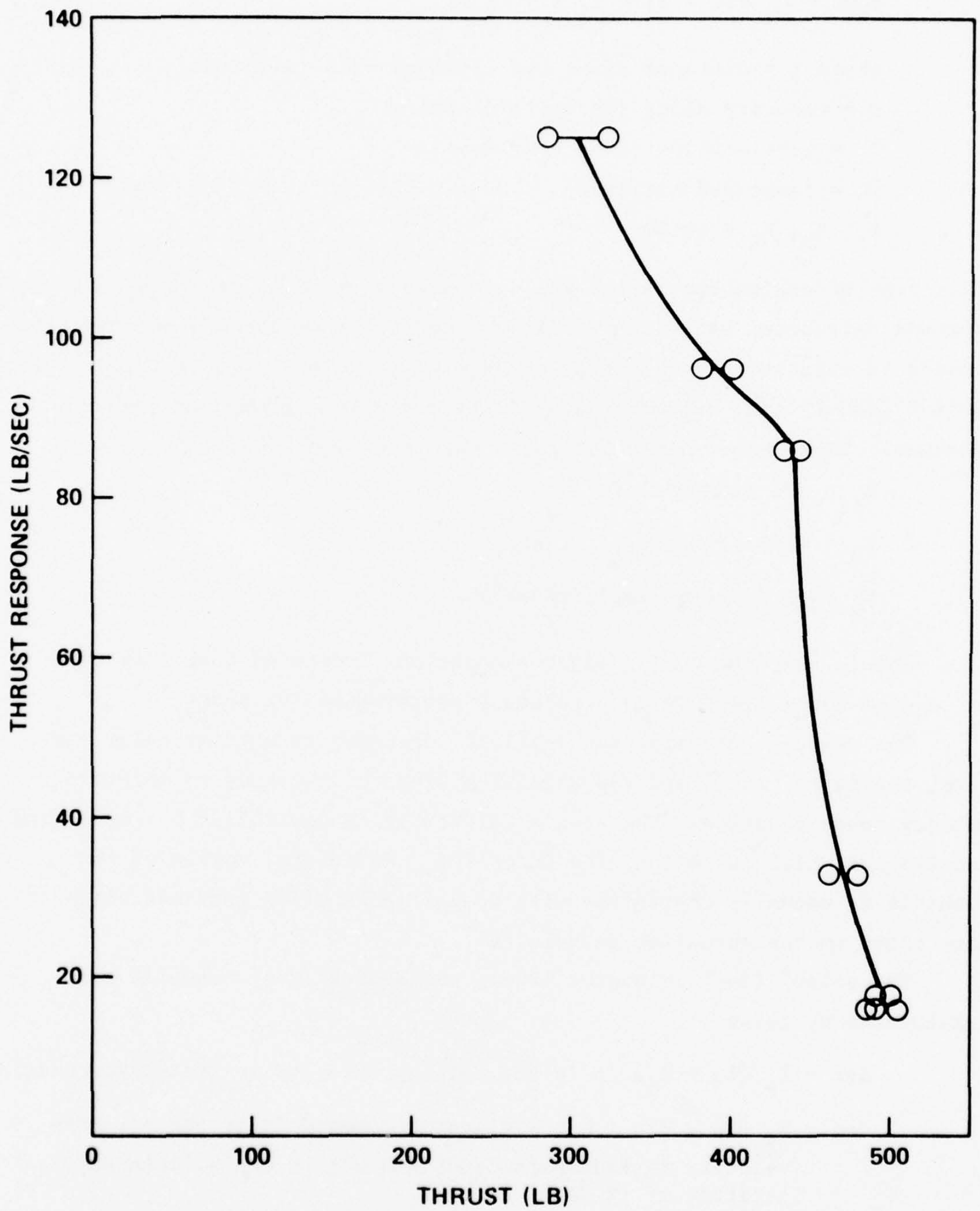

Figure 12 - Maximum Thrust Response Rate of Demonstration Vehicle

$$r\dot{p}mC = K_x\,(XC - X) + K_{\dot{x}}\,\dot{x} + K_{\ddot{x}}\,\dot{u}_o$$

where X = distance along the vertical axis (altitude)

$\dot{x}$ = velocity along the vertical axis,

$\dot{u}_o$ = acceleration along body x-axis

XC = commanded altitude

K_x, $K_{\dot{x}}$, $K_{\ddot{x}}$ = gains

This type of engine controller was used because it does not require a speed command reference. In other words, we need not know the engine speed necessary to support the vehicle as a function of weight. The altitude error term K_x (XC-X) will automatically adjust the speed command as weight changes. The engine controller gains that give the best response are:

K_x = 300 (rpm/sec)/ft

$K_{\dot{x}}$ = -850 (rpm/sec)/(ft/sec)

$K_{\ddot{x}}$ = -1,000 (rpm/sec)/ft/sec^2)

The vehicle response during hover simulations indicated that this type of engine controller yields acceptable performance for hover.[5]

The vehicle autopilot was initially designed to automatically control the pitch, roll, and yaw angular motions of the body to maintain steady hover position. The X-axis (altitude) is controlled by the engine controller which is part of the autopilot. Horizontal motion of the vehicle is manually controlled with proportional stick commands which are added to the autopilot outputs.

The splay* (dsc), elevator (dec), and rudder (drc) commands are calculated by using:

dsc = K_ϕ Q1u + K_pp (p is the rolling velocity in radians/seconds)

dec = K_θ Q2u - Q2c + K_qq - elevator command (q is the pitching velocity in radians/seconds and Q2c is the builtin body attitude of +5 deg)

drc = K_ψ Q3u + K_rr + rudder command (r is the yawing velocity in radians/seconds)

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*Splay is the combination of four vane deflections to control vehicle roll motion.

The K terms are gains for roll (ϕ), pitch (θ), and yaw (Ψ) motions defined later. Q1u, Q2u, and Q3u are approximate roll, pitch, and yaw errors.

Individual fin commands are then formed by using (viewing from behind the vehicle):

TopC = dsc-drc

BotC = dsc+drc

RightC = dsc+dec

LeftC = dsc-dec

These commands are then limited to the $\pm$15-deg vane position limit, that is,

$|TopC| \leq 15$ deg, etc.

A model of the Solactor actuator used for deflecting the vanes was employed to determine the actual vane position. This actuator model is a first order model with a time constant of 0.1 sec and a slew rate limit of 100 deg/sec. From these vane positions, the effective elevator (de), rudder (dr), and splay (ds) angles were calculated as:

de = (Right-Left)/2

dr = (Bot - Top)/2

ds = (Top + Bot + Right + Left)/4

The vehicle simulation was utilized in an analysis to determine the best set of autopilot gains. These gains are as follows:

$K_\phi = 1$ deg/deg

$K_p = 1$ deg/deg/sec

$K_\theta = K_\Psi = 2$ deg/deg

$K_q = K_r = 1.5$ deg/deg/sec

$K_z = K_y = 1$ deg/ft

$K_{\dot{z}} = K_{\dot{y}} = -3$ deg/ft/sec

In normal hover maneuvers, the parameters $\phi C = \theta C = \psi C = 0$. Maneuvers are initiated by commanding XC (engine controller), YC, and ZC. An

early simulated hovering maneuver was formulated to illustrate the vehicle response when these gains are used. This maneuver simultaneously commands both A (horizontal) and X (vertical) displacements. The initial conditions are:

X = -20 ft

Z = -20 ft

θ = +30 deg (pitch angle)

Thrust = 560 lb (vehicle weight)

The vehicle is commanded to the position X = Z = 0. That is, the maneuver causes 20-ft X- and Z-displacements to be commanded with the pitch angle initially 6.2 deg in a direction opposite to the intended motion. The response to this maneuver command for a cg location of 88.7 in. is given in Figure 13. In general, the response was good. However, the horizontal displacement was 22.6 ft, not zero as commanded because the thrust/cg offset caused a nose-down torque and a 10-deg pitch vane setting was required to trim this torque. In automatic hover flight, a bias 22.6-ft horizontal displacement would correct this effect.

Because of accelerometer misalignments, self-level errors, and an assortment of other inertial package errors, automatic position keeping was not feasible. Simulation of operator response to vehicle motion shows that manual stick control of Y- and Z-positions is the most practical solution to position control. The hover control flow chart is shown in Figure 14.

TETHERED HOVER FLIGHT TESTS AND RESULTS

The tethered hover flight tests began at DTNSRDC during the summer of 1976. A trapeze support bar was attached to the nose of the vehicle to allow it to be supported in the vertical attitude by a crane. With the vehicle in this attitude, the hover capability of the autopilot/jet vane was observed.

A control cable attached to the vehicle allowed override commands to provide translation fore and aft and sideways, rotation about the vertical axis, and vertical motion to measure liftoff capability. An electric power cable and an instrumentation cable were also provided.

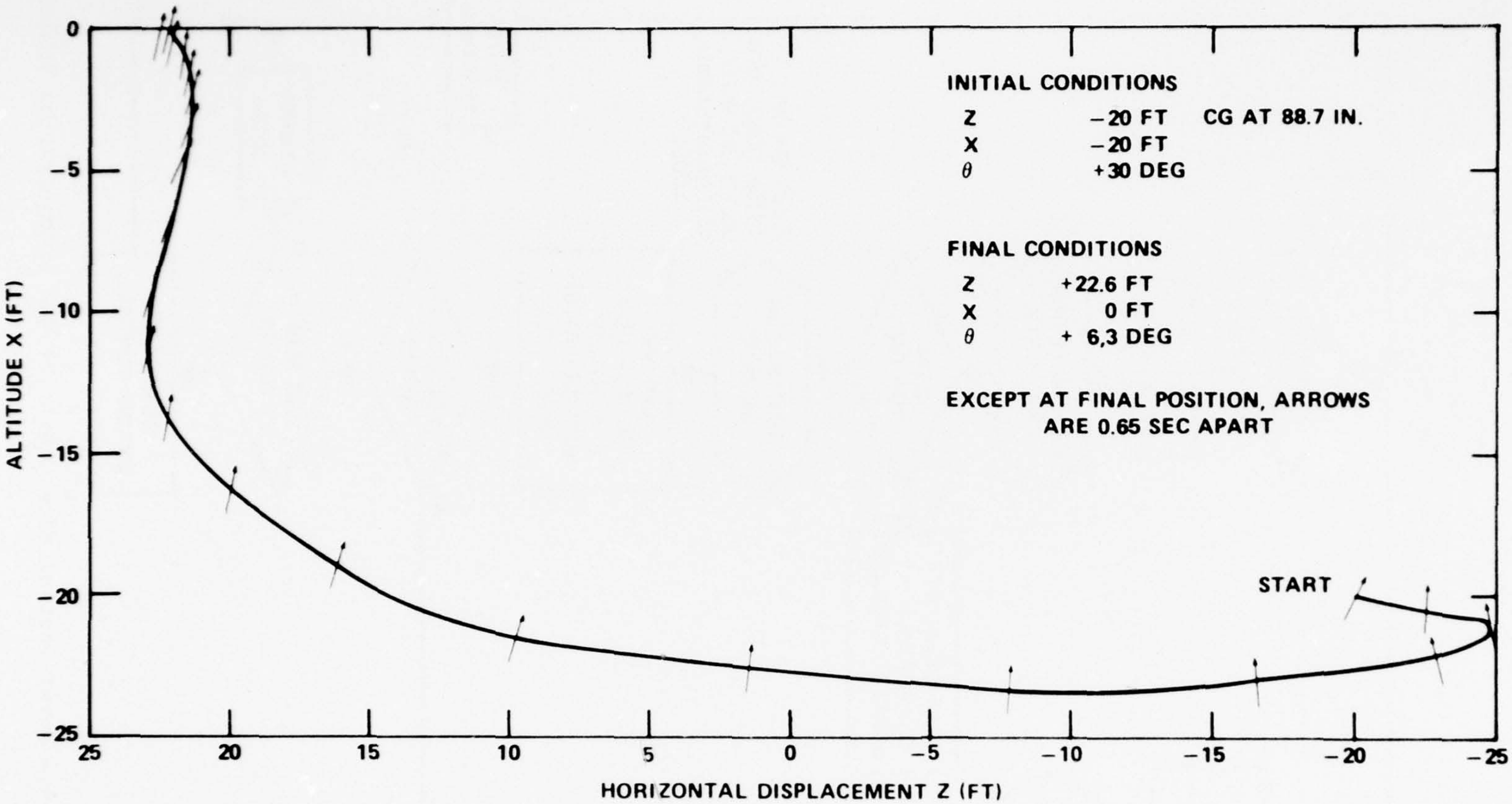

Figure 13 - Hover Maneuver with Attitude Inidcated

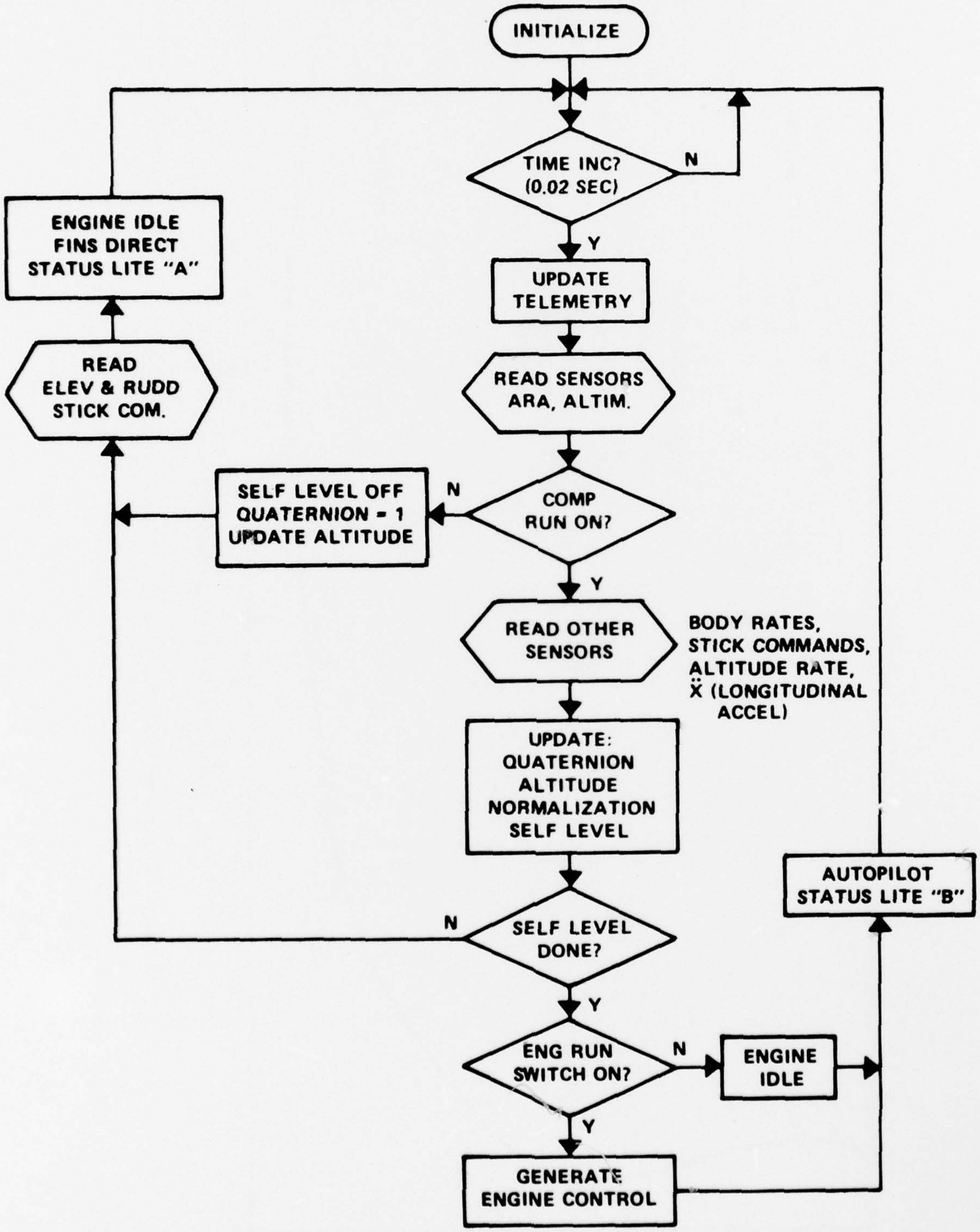

Figure 14 - Hover Control Flow Chart for the Demonstration Vehicle

A Brush recorder monitored in real time the engine rpm, and exhaust gas temperature, engine speed command, and radar altimeter reading of altitude. All four vane positions were recorded as well as the vehicle weight via a load cell between the crane hook and the trapeze support bar. Vehicle attitude was determined by an inclinometer and also recorded.

Control of the RPV was from a control console through the use of an umbilical cable attached to the vehicle. The umbilical cable passed from the vehicle J box up the crane support cable, down the crane boom and over to the console for control operations. The ground controller could send an emergency STOP command to the vehicle engine in case of a malfunction.

The Teledyne YJ402 turbojet was started by compressed air (700 psi) in a horizontal attitude on the trailer. A pyrotechnic ignitor was used for ignition at 8000 rpm. After ignition and attainment of idle rpm, the air supply was manually disconnected. The vehicle was then raised to the desired test attitude (90 deg) by a hydraulic lift on the trailer/erector. The engine rpm was then increased until hover was obtained.

A trailer/erector was so designed that the engine could be started with the vehicle in a horizontal attitude and then rotated vertically for the tethered hover tests; hover flights were performed. Figure 15 shows the hover test site with the demonstration vehicle mounted on the trailer/erector in the vertical attitude.

The trailer used was a modified farm ("hay") wagon. The hydraulic lift normally used to raise the wagon about 30 deg was moved further aft to allow the trailer bed to rotate to a vertical position (90 deg). A 10-hp hydraulic pump was used to power the hydraulic lift. A remotely located control box allowed support personnel to raise and lower the trailer at a safe distance while the jet engine was operating. The jet exhaust was deflected 90 deg (away from the trailer) by a sheet metal duct mounted on the concrete pad just behind the trailer.

While the vehicle was in a horizontal attitude on the trailer, its forward motion was restricted by wooden chocks in front of the main gear wheels and the nose wheel. Rearward motion was restricted by the cable supported by two I-beam posts mounted at the sides of the trailer. A hook on the nose gear strut engaged the cable.

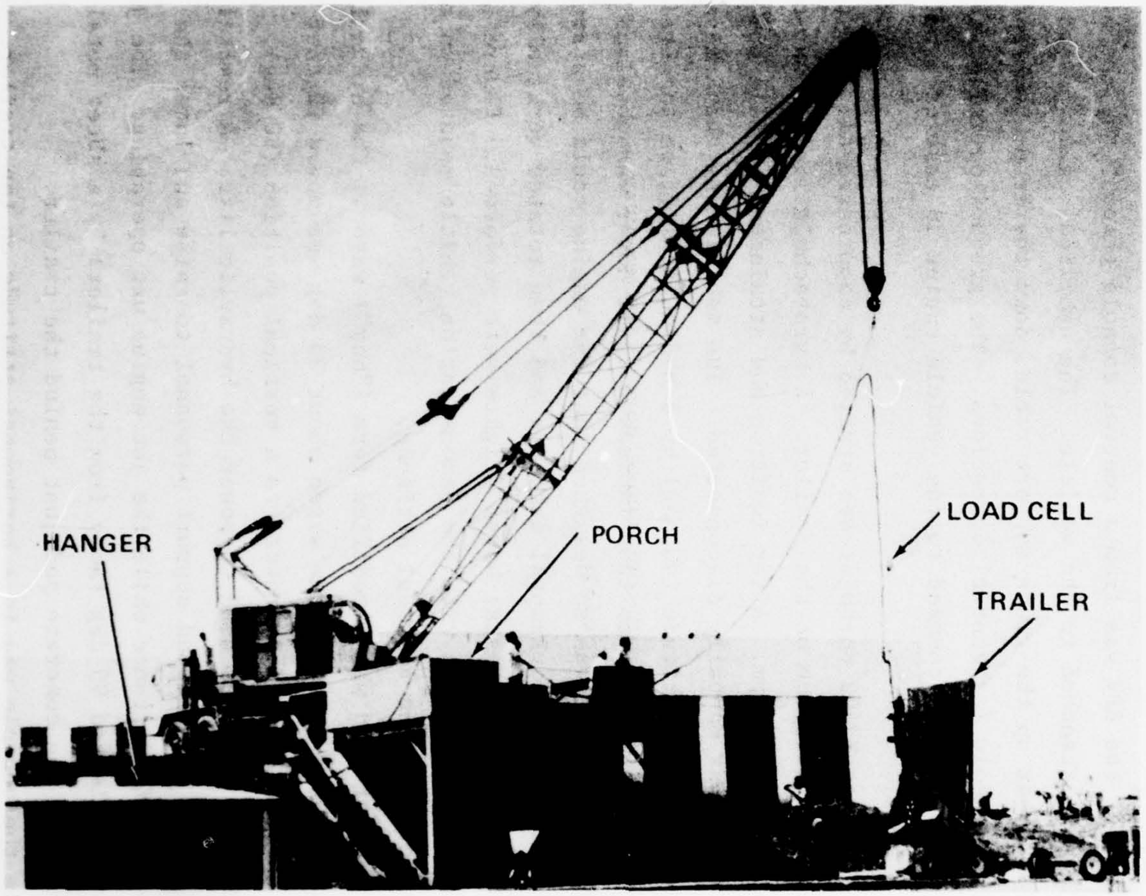

Figure 15 - Demonstration Vehicle at Hover Test Site
(Trailer at 90 Degrees)

When the trailer reached 90 deg attitude and the crane operator started lifting the vehicle via the trapeze support bar, the vehicle moved far enough away from the trailer so that the wheels cleared the wood chocks during liftoff.

The crane operator was directed to move the vehicle from the trailer to the test area about 20 ft behind it. The crane was located about 15 ft above the trailer, just behind a concrete "porch" at whose base was located a concrete pad that extended over to the trailer. This concrete pad was used to deflect the high velocity jet exhaust during the tests. The height of the porch also allowed the vehicle to be tested at an altitude high enough to eliminate recirculation of exhaust gases. This height enabled the vehicle radar altimeter to operate more efficiently since it tended to have trouble "locking on" at heights below 10 ft.

During the hover tests, the vehicle was positioned in front of the porch and about 3 ft above its sheet metal fence. At this location, tether lines (originally fastened to the main gear struts and later moved to the ends of a bar attached to the upper surface of the wing) were locked by using sailboat line cleats at a location about 50 ft behind the trailer. These lines were used to control the roll attitude of the vehicle during liftoff (and docking) from the trailer; they were released while the hover tests were being performed to remove any chance of interference in controlling roll attitude.

Fuel for the vehicle was supplied remotely from the 42-gal drum used in the cradle tests. This allowed extensive engine run capability without fuel depletion (vehicle fuel capacity was only 12 gal) and also reduced to 460 lb the weight of the vehicle during these hover tests. The boost fuel pump, normally located in the vehicle, was removed to the fuel barrel after it was discovered that suction pressure on the fuel hose was causing it to collapse and starve the engine. A turbine flowmeter measured fuel flow during the tests.

The 28-Vdc electric power required by the vehicle was also supplied externally by using two battery packs of 65 amp-hr capacity. Two power supplies were used to recharge the battery packs. The 80-ft power cable IR drop was several volts and regulated power supplies were used to maintain the voltage at the vehicle within 26 to 28 Vdc during the tests.

The instrumentation cables, electric power cables, and fuel line were tied together; they were fastened to the porch at one end and to the crane hook at the other end. From there they ran along the vehicle support cable to the trapeze support bar and then connected to the vehicle on the underside of the fuselage. (The lower panel of the fuselage was removed for these tests.) The load cell in the vehicle support cable registered 460 lb (at zero thrust) of load, indicating minimal cabling interference with the vehicle. In hover, as the trapeze support bar swung from a vertical attitude toward a horizontal attitude, the load cell registered the unsupported weight of the cabling and support bar (which was 10 to 15 lb).

Before successful hover flight was achieved, 13 runs (engine starts) were made. Most of the early runs were shakedown tests involving problems associated with tethered line rigging, engine fuel starvation problems, and autopilot control operation. Three Teledyne engines were used. The first failed (during the second run) on its fourteenth start when the turbine failed. This engine had previously been used during the cradle tests and also at NWC (China Lake) during engine installation tests.[3] The internal fuel metering valve of the second engine failed during Run 8.

The third engine ran successfully for the remaining runs for a total time of 104 min, mostly in the vertical attitude. This is remarkable since the engine bearings are grease packed and the engine is normally restricted to 30 min of operation (at full thrust). The fact that the engine was operating well below maximum rpm most of the time probably accounts for its extended lift.

Tethered hover flight was successfully achieved (Figure 16) on 29 September 1976. The vehicle was moved to the test position, the tethered lines were released and the "computer run" switched on at the control console. After the gyroscope self-leveled light came on, the engine speed toggle switch on the control console was switched to "Run." Since prior to this time the crane supported the vehicle, the autopilot does not change engine speed until an altitude increase is commanded. This was accomplished next by briefly moving the control stick for altitude

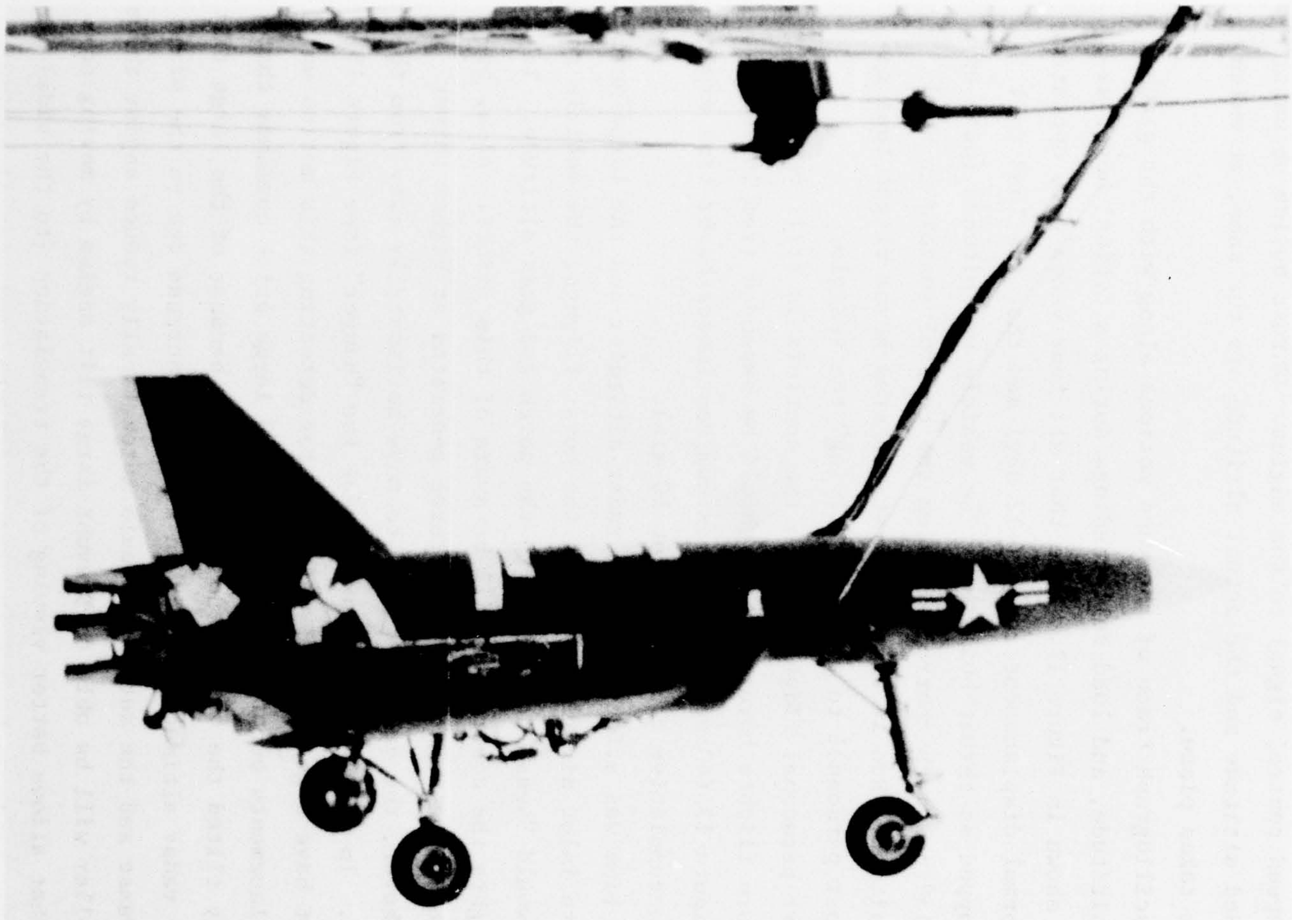

Figure 16 - Demonstration Vehicle in Hover Flight, Run 14
(Note angle of trapeze support bar)

control in the UP direction since the control stick sends an altitude rate command. At this time, the radar altimeter senses an altitude that is lower than the commanded altitude and the MGU autopilot sends an engine speed control signal to the engine. Thrust builds up until the commanded altitude and the actual altitude are the same, at which point hover takes place.

The oscillograph trace of the vane motions along with the pitch attitude, altitude, and load cell readings during a typical hover sequence are shown in Figure 17. Note that all four vanes were operating in their normal displacement range ($\pm$12 deg) and that the load cell reading dropped as thrust built up. The vehicle was pitched (nose up) slightly via the pitch control stick on the control console to hold vehicle position. Run 14 was the first tethered hover flight that enabled support personnel to practice "flying" the vehicle.

Support personnel flight time on the controls is still very low, and in future flights hover control should be expanded from 16 sec shown in Figure 17 (40 sec was the maximum continuous hover time experienced and accumulative time was about 10 min).

Hover time was affected by the radar altimeter and the large normal force due to inlet air flow. During the hover flights, the vehicle radar altimeter would "sense" closeness to the porch and gain altitude. In future flights the controller will be aware of this effect. Also, because of the large negative normal force generated at higher thrust levels in hover, the vehicle tended to move horizontally away from the controller. In Run 14 he was just inside the "hanger" (see Figure 15) and did not have a good visual reference for detecting this motion until large displacements occurred. This required large stick commands that excessively tilted the vehicle nose up. Then, because of the large tilt angle, the radar altimeter sensed an altitude increase due to the slant range increase and the autopilot would automatically reduce engine thrust. The controller will be able to prevent large tilt angles by moving to a location that allows better viewing of the translation (to the side).

It is possible to bypass the radar altimeter and control engine rpm manually. This will be attempted in future tests to determine

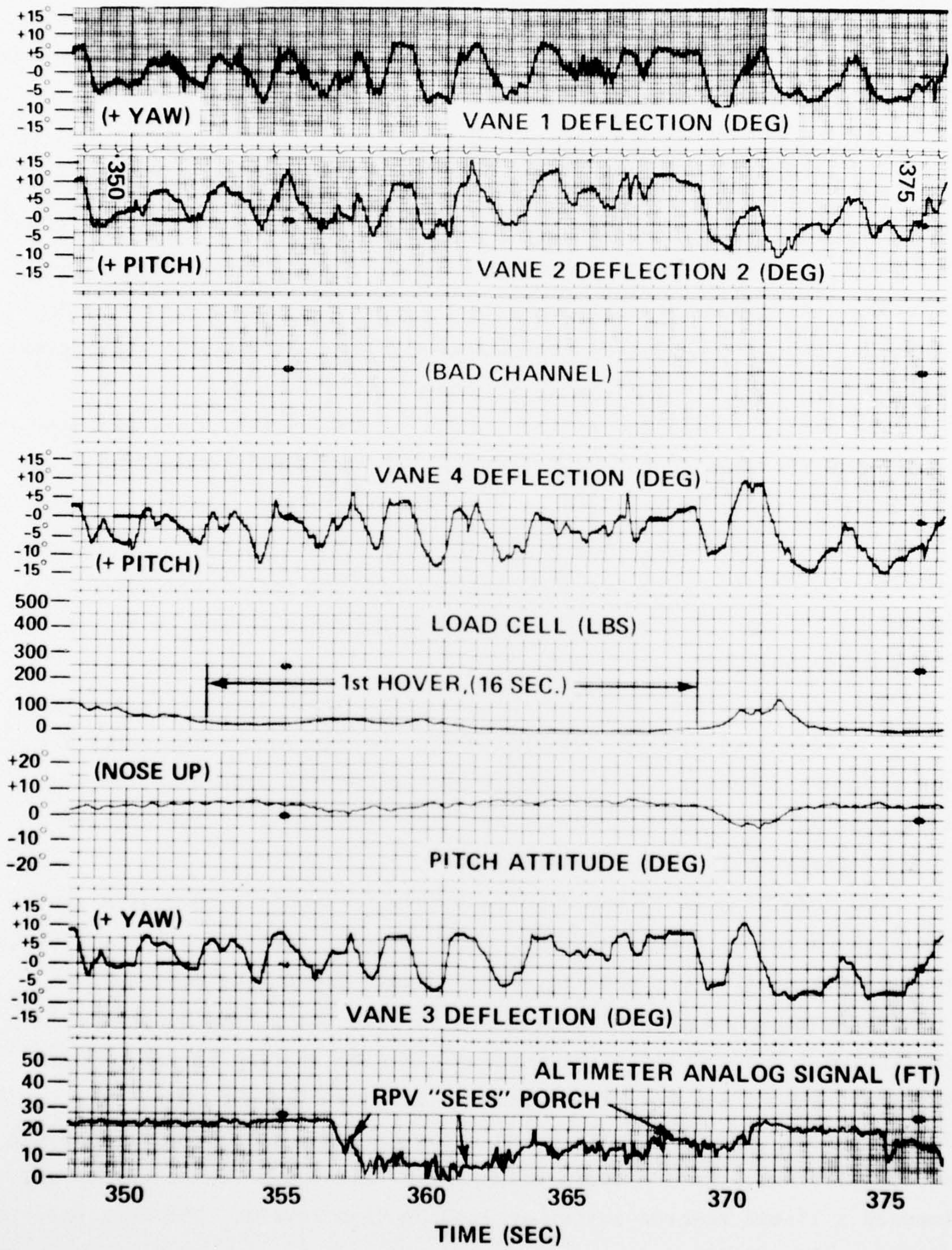

Figure 17 - Brush Recorder Data during Hover, Run 14

whether it provides better control over vehicle altitude. In future tethered hover flights, attempts will also be made to dock and takeoff from the trailer. Later, free-flight hover on land will be attempted prior to shipboard test operations.

RPV MISSION CAPABILITIES

The current demonstration vehicle was designed and constructed by using conservative design practices at DTNSRDC. An RPV mission-capable design of the same size would make extensive use of Kevlar or similar materials to reduce the airframe weight. Estimates indicate that the airframe structure could be cut to about 110 lb. This would allow more fuel to be added to extend range or endurance.

The use of a turbofan engine instead of the turbojet now employed could also increase range considerably. The Williams F107-WR-100 turbofan engine, presently utilized for the Tomahawk cruise missile, could easily be adapted to fit this airframe. Its weight (128 lb) is comparable to that of the turbojet (125 lb). Installed, sea level takeoff thrust is 598 lb. For a 560-lb takeoff weight, the thrust to weight ratio would be 1.07.

Use of the Harpoon MGU for the autopilot would facilitate changes to the computer to simulate several different missions. The autopilot and such other electrical components as the control actuators, data link, navigation systems, and wiring weigh about 90 lb. The current size airframe could carry 160 lb of fuel.

The remaining 72 lb would be available for sensors such as a search radar and a FLIR. Combinations of other sensors could also be utilized, e.g., laser designators and electronic signal monitoring devices.

Performance capability of the vehicle with the turbofan engine is impressive. Table 2 lists the various times on station for 85 nm with vertical takeoff and for 280 nm with an assisted launch. Note that the dash speed is considerable (400 kt) allowing rapid response in the event of hostilities. These mission calculations allowed a 30-sec warmup and imposed a 15-min reserve loiter at landing (sea level). The fuel reserve was 5 percent.

TABLE 2 - MISSION CAPABILITIES

(with 160 lb of internal fuel and 140 lb of external fuel)

	VERTICAL TAKEOFF (Internal fuel only)	CATAPULT (OR BOOSTER) LAUNCH (Internal and External fuel)	
		LONG RANGE	LONG ENDURANCE
Range to Target Area, n. mi	85.0	280.0	85.0
Endurance Time at Target Area, hr	1.0	1.0	3.0
Flying Time to Target, min	14.4	63.0	23.0
Average Speed to Target Area, knots	333.0	296.0	222.0
Dash Speed Capability, knots	400.0	400.0	400.0

NOTES: 1. External fuel can be increased to improve range or endurance on station.
2. At dash speed, time at target area and endurance would be reduced.

CONCLUSIONS

Vertical attitude takeoff and landing (VATOL) offers an attractive solution to the launch and recovery of both Navy RPV's as well as manned aircraft aboard ships. The DTNSRDC VATOL demonstration vehicle provides the Navy with a valuable tool to assess vertical shipboard docking while ships are underway.

Jet vane control for hover flight is also an important concept that was evaluated during the tethered hover flight tests. Analysis indicates that the vanes could also be used for horizontal flight on some configurations, minimizing the need for aerodynamic control surfaces. This would simplify the design of an operational vehicle.

The close-coupled canard delta wing configuration exhibits superior aerodynamic characteristics that are superior to other VTOL concepts. Higher lift generated by the canard results in easier transition from horizontal to vertical flight. This increased lift also allows slower touchdown speeds for conventional runway landings.

The impact of VATOL vehicles on ship operations is minimized in that only the edge of the deck is used for launch and recovery. Ship safety is enhanced in that jet engine exhaust is overboard. A malfunctioning VATOL vehicle would drop clear and not crash on the ship deck.

Finally, the vertical attitude configuration should cost considerably less than other concepts; a dedicated engine development program is not required because only the engine exhaust is deflected for vertical flight. The configuration is light in weight compared to other VTOL concepts.

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